Sustainable pre-fabricated composite housing

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Livros são papéis pintados com tinta.

Estudar é uma coisa em que está indistinta

A distinção entre nada e coisa nenhuma.

(Fernando Pessoa)

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If you want to do a PhD, you need to be lucky with your supervisors. If you want to do a multi-disciplinary PhD, you need to be very lucky with your supervisors! My supervisors were, indeed, excellent. They turned me from an "amateur in field" guy into an "amateur in field" guy who wants to be "familiar with fields". That is why this thesis included lots of learnings. At end, however, I ended up with the Socratic paradox that "I know one thing: that I know nothing". After all, it is not that I feel accomplished or proud of some achievements today; most likely I just want to run away from formalities and say some words more than a "thanks to my professors *et al.* [everything]" to those who let me do this thesis.

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Abstract

Housing is scarce in the world but even more so in Africa. The construction of current housing solutions in Africa is costly and requires extensive amount of time, labor and materials. Moreover, considering the climate, overheating is a big challenge to be tackled in buildings. This thesis aims to develop a sustainable pre-fabricated sheltering and housing solution for developing countries in Africa. Toward this aim, after an initial material screening, defining criteria for material selection and performing relevant tests and analyses, a multi-criteria decision analysis is performed to identify the optimum solution. Subsequently, a building design of the proposed materials (sandwich-structure composite) is compared with a typical masonry building in terms of environmental impacts. After thermal analysis of this building, the impact of different passive cooling techniques is investigated in terms of indoor air temperature and thermal comfort of the occupants. By identifying the most effective solution of each technique, their combination is assessed to attain an optimized design. Next, the implementation of the proposed building is evaluated in rural areas of Nairobi by determining two levels of energy demand and required cooling and heating energy. The feasibility of energy self-sufficiency is then investigated by designing a stand-alone photovoltaic system. Moreover, the impact of supply of load probability on required power of photovoltaic (PV) array is studied by evaluating different PV technologies. The designed system is then compared with an alternative grid extension to evaluate the environmental benefits of this solution. Finally, the life cycle cost of the proposed building is evaluated and compared with a comparable masonry building throughout their life cycle. Different sensitivity analyses are also performed to assess the influence of parameters such as construction cost, climate and discount and inflation rates. The results demonstrate that the proposed building is a sustainable, passive and energy self-sufficient sheltering and housing solution and that these new technologies can be used to significantly improve the lives of a large number of people and communities.

Resumo

A disponibilidade de habitação é escassa no mundo, mais este problema é ainda mais importante em África. Atualmente a construção de habitação em África é dispendiosa e exige uma elevada quantidade de tempo, trabalho e materiais, nem sempre disponíveis. Além disso, considerando o clima, o superaquecimento interior é um grande desafio para a construção. Esta tese tem como objetivo desenvolver uma solução de abrigo e habitação pré-fabricada sustentável para os países em desenvolvimento em África. Para este atingir este objectivo realizou-se, após uma triagem inicial de material, definição de critérios para a seleção de materiais e execução de testes e análises relevantes, uma análise de decisão multi-critério com vista a identificar a melhor solução construtiva. Posteriormente, um conceito de construção utilizando os materiais propostos (material compósito em estrutura sanduíche) é comparado com um edifício de alvenaria típico em termos de impactos ambientais. Após análise térmica do edifício, é investigado o impacto de diferentes técnicas de arrefecimento passivo em termos de temperatura do ar interior e conforto térmico dos ocupantes. Após identificar a solução de engenharia mais eficaz para cada uma destas técnicas, a sua combinação é avaliada no contexto de um projeto otimizado. Em seguida, a implementação do edifício proposto é avaliada em áreas rurais de Nairobi, determinando dois níveis de necessidade de energia para refrigeração e para aquecimento. A viabilidade da auto-suficiência energética é então investigada no contexto de desenvolvimento de um sistema fotovoltaico autónomo. Além disso, o impacto da probabilidade de fornecimento de carga na definição da potência fotovoltaica necessária é estudado. O sistema projetado é então comparado com uma alternativa de extensão de rede para avaliar os benefícios ambientais desta solução. Finalmente, o custo do ciclo de vida do edifício proposto é avaliado e comparado com o de um edifício de alvenaria em todo o seu ciclo de vida. Análises de sensibilidade diferentes também são realizadas para avaliar a influência de parâmetros como custo de construção, o clima e taxas de inflação. Os resultados demonstram que é possível propor uma solução de habitação passiva e auto-suficiente num contexto sustentável e usar esta tecnologia para melhorar significativamente a vida de muitas pessoas e comunidades.

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CHAPTER 1 INTRODUCTION

"We shape our buildings; thereafter they shape us."

-Winston Churchill

Abbreviations

EDAM	Engineering design and advanced manufacturing
ESD	Engineering systems division
FEUP	Faculty of engineering of University of Porto
GHG	Greenhouse gas
IEA	International energy agency
INEGI	Institute of science and innovation in mechanical and industrial engineering
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LCIA	Life cycle impact assessment
MCDA	Multi-criteria decision analysis
MIT	Massachusetts institute of technology
NPV	Net present value
PV	Photovoltaic
SAPV	Stand-alone photovoltaic
UN-Habitat	United Nations human settlements program

1.1 Framework

This thesis was carried out under the framework of MIT-Portugal PhD program "Leaders for Technological Industries" with focus on "Engineering Design and Advanced Manufacturing (EDAM)". The MIT-Portugal is an international collaboration between the government, academia and industry in Portugal and Massachusetts

Institute of Technology (MIT) to develop education and research programs related to engineering systems. The ultimate aim of EDAM program is to integrate science and advanced technology for product development within a social and economic context [1]. Toward this, the PhD student is primarily challenged to lead an industrial need, determined by a technological company. Consequently, the thesis development is initiated with a "learning" phase acquired through internships. Afterwards, considering the required developments by the industrial partner and evolved findings during the investigations, the thesis is developed meeting the needs of both industry and academia.

The industrial partner of this thesis was "N2Build", a start-up company based in Portugal that intended to develop a novel sheltering and housing solution for developing countries, particularly in Africa. The thesis development was performed during a period of 3 years consisting of a one year internship period and two years of research and development. Considering the start-up stage of the industrial partner, the internship was carried out at different research centers namely, 1) Institute of science and innovation in mechanical and industrial engineering (INEGI); 2) Department of Mechanical Engineering, Faculty of Engineering of University of Porto (FEUP); and 3) Efacec. The research and development part was also carried out at FEUP and INEGI as well as the Engineering Systems Division (ESD) at MIT.

1.2 Motivation

According to the United Nations human settlements program (UN-Habitat) [2], 40 % of the global population, i.e. 3 billion, will live in inadequate housing by 2030. Most of these people are expected to be in developing countries, particularly in Sub-Saharan Africa. According to the latest report by the United Nations in 2015 [3], it is predicted that quarter of world in 2050 will be Africans. This ratio would increase to 39 % in 2100 [4]. In spite of this tremendous increase in population, the number and growth of the required housing are narrow. In addition to overpopulation, other factors such as national disasters and wars have led to consider developing novel sheltering and housing solutions for this region.

There are numerous problems in the current housing solutions of this region. Their construction is normally costly, and requires extensive amount of time, labor and materials. Moreover, considering the high outdoor air temperature, overheating is one of the main challenges to be tackled in these buildings. Consequently, there is a considerable amount of energy being used for air conditioning. This makes it challenging to achieve a passive house design which is recognized with little energy demand for air conditioning [5]. Furthermore, means of supplying energy for basic needs of the occupants such as lighting, are normally conventional and associated with high cost and environmental impacts. According to the international energy agency (IEA) [6], about 1.5 billion people in the world do not have access to electricity yet. In sub-Saharan Africa, 69 % of population lack access to the electricity grid [7]. In Kenya, for instance, while 74.8 % of population live in rural areas, only 8 % of them have access to electricity [8,9].

Pre-fabricated home which has also been addressed with the terms such as off-site constructed, prefab, modular, pre-manufactured and pre-built home was firstly appeared in the 1920s. Advantages such as rapid construction, better quality, reduced need of resources and less waste have led to an increase in pre-fabricated housing [10]. Linking this with the massive need for sheltering and housing in Sub-Saharan African countries, pre-fabricated buildings can be a suitable solution. However, there are several technological and social aspects on their implementation that must be taken into consideration.

After evolving the concept of sustainable development in 1987 as “a development that meets the needs of the present without compromising the ability of future generations to meet their own needs”, it became a major area of interest within different areas. By taking into account three interconnected rings of economy, environment and society, sustainability is one of the main requirements of a successful business in the 21st century. Considering the discussed needs and problems associated with current sheltering and housing solutions in African countries, novel buildings (such as pre-fabricated ones) can contribute in sustainable development of this region significantly.

1.3 Research question

In the context of the needs of the African countries, the aim of this research is to develop a sustainable pre-fabricated housing solution. Consequently, the main research question for this study is defined as:

“Can pre-fabricated buildings be sustainable solutions for housing in Africa?”

Buildings are complex systems consisting of different components. Thus, in order to answer the research question, different fields of science must be taken into consideration. Linking this to what were discussed in the former section regarding the problems of current housing solution, the research question was broken down to three following sub-questions:

- Sub-question 1: *"what technologies can be used to fabricate such buildings?"*

As being pre-fabricated was addressed as one of the essential specifications of the building, development of its structure is the primary sub-question to be answered. This requires investigating different technologies for the structure in order to determine the relevant criteria, alternatives and eventually the optimum solution.

- Sub-question 2: *"Can this solution be a passive house?"*

As discussed, huge amount of cooling energy demand is a big challenge to be tackled in buildings of Africa. Therefore, the possibility of attaining passive design to provide thermal comfort for the occupants with the least possible energy use is another vital issue to be investigated in this study.

- Sub-question 3: *"Can this building be energy self-sufficient?"*

The notable portion of African population lives in urban areas where access to electricity grid is difficult and costly. Consequently, conventional resources of energy are being used that are neither cost-effective nor environmentally friendly. Therefore, another important issue to be taken into investigation for the studied building is possibility of integrating sustainable means of energy independently from the electricity grid.

1.4 Research design

After defining the research question and sub-questions, the research procedure to answer them must be determined. There are various aspects at needs side of this study (i.e. sustainability and housing requirements in Africa) that must be interpreted and correlated to the product (i.e. building). As mentioned before, sustainability is based on three pillars of economy, environment and society. Moreover, analysis of buildings itself engages broad fields of science such as design and architecture, building materials, thermal behavior, energy performance, energy supply and etc. Thus, taking into consideration these requirements and research questions led to define product development steps in this study.

To answer the first sub-question, structure development is considered as the first step of product development. Afterward and in order to evaluate the environmental needs of sustainability, the building made of the proposed structure must be assessed in terms of environmental impacts. Moreover, addressing the second sub-question and social needs of sustainability, thermal performance of the proposed building needs to be inspected in the next step. Subsequently, looking for an answer to the third sub-question, energy demands of the occupants and means of energy supply must be taken into consideration. Evaluating the costs associated with different phases of building life cycle completes the sustainability assessment by addressing its economic dimension. Fig. 1.1 shows how the requirements are interpreted in order to define the main steps of product development in this study. It is worth noting that the arrows imply the flow of translating demands into the product development steps and do not represent the correlations among different items.

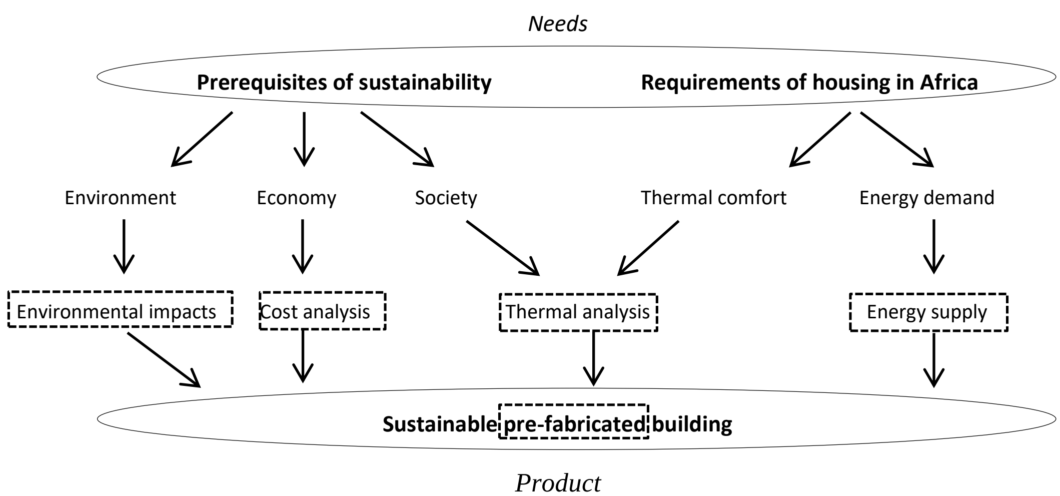

Fig. 1.1. Interpretation of needs to determine product development steps in this research

1.5 Thesis outline

As it was identified in the research design, the five main product development steps in this study are structure development (pre-fabricated), environmental impact assessment, thermal analysis, energy analysis and cost analysis. Regarding the thesis structure, one chapter was dedicated to each of these steps as it is illustrated in Fig. 1.2. This thesis is formed as an article thesis meaning that the content of all chapters except chapters 1 (introduction) and 7 (conclusions) have already been published or are under submission in scientific journals and conferences at the time of thesis submission. This formation is designated to allow readers with different fields of interest to look at these chapters independently from each other. Therefore, repetition of some contents, such as design of the proposed buildings, in different chapters was unavoidable. In following sections, the background, approach and content of each chapter, i.e. each product development step, are introduced briefly.

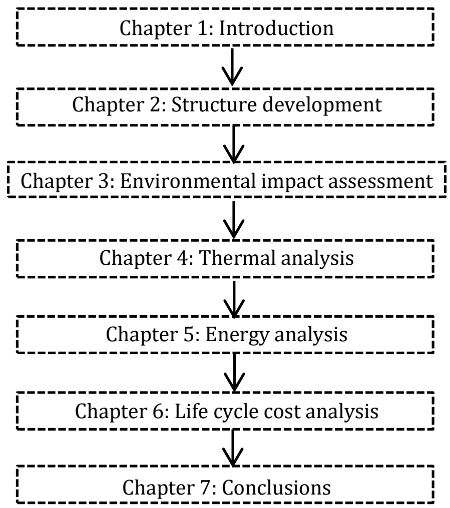

Fig. 1.2. Thesis outline

1.6 Structure of the pre-fabricated building

Material selection is a key step in product design and normally aims to identify the most suitable material that meets product performance goals at minimum cost. As discussed before, there is a growing trend toward pre-fabrication construction. Moreover, there is an increasing interest in using composite wall systems in pre-fabricated building due to their lower environmental impact, light weight and lower energy consumption [11]. Sandwich composite panels are special class of composite materials that are fabricated by attaching two thin but stiff skins to a lightweight but thick core. The core material normally has low strength, but its higher thickness results in high bending stiffness with overall low density.

Concerning numerous advantages of sandwich-structured composites, they are considered for the structure of the proposed building. As it is explored in chapter 2, after an initial material screening, five different materials are selected and compared in terms of mechanical, thermal, acoustic and fire performance as well as cost and environmental impact. This consists of mechanical and fire testing of the selected materials, obtaining their thermal and acoustic properties and performing a cost analysis and environmental impact assessment. The results of the tests and analyses led to a multi-criteria decision analysis (MCDA) which is determined by pairwise comparisons of alternatives. Finally, the proposed solution is compared with a typical masonry wall in terms of the studied criteria for material selection.

1.7 Environmental impact assessment

Environmental impacts are one of the main concerns and prerequisites of sustainable development. Buildings account for up to 30% of greenhouse gas emissions [12]. Life cycle assessment (LCA) has been the most popular tool to evaluate environmental performance of a product over its entire life cycle. In the building sector, LCA has been the subject of many studies mostly aim to highlight energy and environmental impacts associated with different phases of life cycle. In these studies, normally the functional unit of assessment was set to a unit of area or the whole building. However, the “whole building” has been usually referred to the entire building, but without its foundation. Regarding the considerable amount of materials and energy used for foundations and their impacts on energy consumption and environmental impacts, taking them into consideration seems to be vital in environmental impact assessment of buildings.

Chapter 3 aims to evaluate the proposed sandwich-structure composite in terms of environmental impacts in comparison with a masonry structure. In chapter 2, the proposed structure is compared with a masonry structure in terms of different characteristics, including environmental impacts, by considering a functional unit of 1 m^2. In chapter 3; however, the comparison is based on the whole building assessment including the required foundations. Toward this aim, a 30 m^2 one story building is considered made of both alternative structures. The design of the building is based on current housing solutions for a family of four people. For the pre-fabricated building, all exterior and interior walls, floor and roof are composed of the proposed composite structure (developed in chapter 2) and the construction of the masonry building is based on a typical Portuguese house in accordance with Eurocode standards. The inventory of each building is firstly determined through an inventory analysis. Afterwards, the life cycle impact assessment (LCIA) is performed to determine the environmental impacts of both buildings at three categories of human health, ecosystem quality and resources.

1.8 Thermal analysis

In spite of high importance, social aspect has been neglected in several building sustainability assessments; especially in those that have focused on environmental impacts. The comfort of occupants is a vital issue that must be regarded in building design and development. Evaluating the thermal comfort of the occupants completes the sustainability assessment of the proposed structure by adding social dimension to the (formerly studied) economic and environmental assessments. Moreover, as mentioned in the research design, the indoor air quality of building is one of the main problems of current housing solutions in African countries. Considering the high outdoor air temperature in this region, overheating in buildings is a big challenge that needs to be tackled. Thermal analysis can demonstrate the thermal performance of building structure and highlight its advantages and drawbacks.

Thermal analysis of the proposed pre-fabricated composite structure is explored in chapter 4. Toward this, the building is initially located in Porto (for comparison with current solutions and knowledge) and a scenario is defined for the occupants, lighting and home appliances (i.e. internal gains). Consequently, the thermal performance of the building is inspected with regard to variations of indoor air temperature of living room and sleeping room throughout the year. Afterwards, the average indoor air temperature is calculated for three coldest and hottest days of year. As overheating is addresses as one of the main problems to deal with, different passive cooling techniques are analyzed to cool the building by natural means. Subsequently, impact of different types of shading, natural ventilation, cool painting and increase in thickness of the interior gypsum plaster are evaluated by calculating different indicators of indoor air temperatures. Eventually, the best solution of each passive cooling technique is compared in three climates of Porto (as representative of warm-summer Mediterranean climate), Mumbai (where there is a high potential need for post-disaster sheltering and as representative of tropical climate) and Nairobi (where 60 % of the population lives in informal dwellings and as representative of Sub-Saharan African countries). These comparisons are conducted in terms of average indoor air temperature as well as thermal comfort of the occupants. The thermal comfort is assessed in accordance with adaptive comfort models of ASHRAE 55 and EN 15251 standards by considering different acceptability limits. Furthermore, additional factors such as heat storage energy, annual solar radiation heat again and surface temperature are inspected to explain causes and effects associated with the studied passive cooling techniques.

1.9 Energy analysis

As discussed before, polluting and expensive energy resources are currently used in many buildings in rural areas of Africa. This is not only due to the cost of electricity, but also unfeasibility of access to the grid in many zones. Considering high solar energy potential and numerous advantages of photovoltaic (PV) systems, they are considered as the best sustainable energy resource for electrification of buildings in this region. PV systems are categorized into the grid-connected and off-grid ones. Considering the objective of this study to develop a solution for both sheltering and housing purposes and actual complications of access to the grid, the off-grid systems (also known as stand-alone PV (SAPV) systems) seems to be a more feasible and advantageous solution.

Chapter 5 aims to present a comprehensive approach for electrification of sheltering and housing solutions in remote areas by taking into account both energy demand and supply sides. After the structure development (which is explained in chapter 2) and its optimization through combining passive cooling techniques (that is described in chapter 4), energy demand of the building must be defined. Consequently, the building is located in rural areas of Nairobi, Kenya concerning the massive need for sheltering and housing and lack of electricity access. Subsequently, two levels of energy needs, one for basic needs and one for ordinary needs, are defined for the required home appliances and lighting. Besides, annual cooling and heating energy demands to keep the occupants within the comfort temperature are calculated and compared for each of the studied passive cooling techniques. After identifying the energy demand and decreasing it through passive cooling techniques, a SAPV system is designed through sizing of the main components as well as determining the optimum tilt angle and azimuth for the PV array. Moreover, the impact of supply of load probability on required power of PV array is investigated by evaluating four PV technologies. Finally, for each PV technology, the greenhouse gas (GHG) emissions of the SAPV system are compared with an alternative grid extension system to highlight the environmental benefits.

1.10 Life cycle cost analysis

Economy is another crucial aspect of sustainability that must be taken into consideration. There are several costs associated with any building during its lifespan. Moreover, there are different individuals such as owners, occupants, constructors, investors, etc. having their benefits and considerations about the most cost-effective building design. Life cycle cost analysis (LCCA) is an effective tool at design and retrofitting levels to assess the total cost throughout the building life cycle. In spite of adversity in cost analysis and dynamic alterations of the costs in construction sector, LCCA is highly beneficial in determining the contribution of different phases in the total life cycle cost.

Chapter 6 aims to evaluate the life cycle cost of a building made of the proposed pre-fabricated structure in comparison with a masonry building by considering four phases of construction, operation, maintenance and demolition. The optimized structure of the building after applying passive cooling techniques is also used for this analysis. Besides, the comparable masonry structure is defined based on Portuguese regulations on energy performance of residential buildings and heat transfer coefficients of building envelope (which assumes that European quality requirements are a good basis for the definition of quality in Africa). Toward this, the share of different building components in total construction cost is primarily calculated based on United States and European costs. This was done because of the global nature of this development and also because of the higher availability of data related to building costs in prefab housing, for which the US has a larger market. Subsequently, the operation costs to provide cooling and heating energy demands to keep the occupant within the comfort temperature as well as lighting and home appliances are determined. Moreover, the required maintenance costs for both buildings are assessed with regard to the life expectancy of different components. Afterwards, the costs associated with demolition of buildings at the end of life cycle are identified. While the construction cost is related to the current point of time, the costs of three other phases need to be translated to the present time. Hence, net present value (NPV) and inflation rates are utlized to assess the future investments. Finally, different scenarios for the location (each representing different construction costs and climates), discount rate and inflation rates are analyzed to check out the sensitivity of the performed LCCA.

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CHAPTER 2 STRUCTURE DEVELOPMENT

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Abstract

Material selection is a key step in product design and typically aims at identifying the most suitable material that meets product performance goals at minimum cost. In recent years, research has been driven for developing sustainable solutions at competitive costs. This work evaluates the sustainability of advanced sandwich-structured composites for novel housing solutions. Five polymer matrix composite sandwich materials have been selected and compared concerning mechanical, thermal, acoustic and fire performance as well as cost and environmental impact, in order to study both the technical viability and the sustainability of lightweight solutions for prefabricated structural wall panels as well as for new housing; this included mechanical and fire testing of the selected materials. Subsequently, the thermal and acoustic properties of the alternatives were obtained. After performing a cost analysis and environmental assessment, the results of the tests and analyses led to a multi-criteria decision analysis (MCDA); PROMETHEE II (preference ranking organizational method for enrichment evaluation) was used to identify the best alternative. Finally, the proposed solution was compared with a typical brick house performance. Higher specific strength, better thermal insulation and lower environmental impacts arose as the main advantages of the proposed structures while acoustic properties and fire safety still need to be improved.

Keywords: Environmental impact; life cycle assessment; sandwich panel; sustainable building; ReCiPe; PROMETHEE II

Nomenclature:

$d_j(a_1,a_2)$	Deviation between values alternatives a_1 and a_2
f	Frequency [Hz]
$\mathrm{F_j}(d_\mathrm{j})$	Preference function
f_b	Normalized mean compressive strength of units
f_k	Characteristics compressive strength of the masonry
f_m	Compressive strength of the mortar
$g_j(a_j)$	Value of alternative a_j
K	Constant for compressive strength
m_s	Mass per unit area [kg·m^{-2}]
M	Number of criteria
N	Number of alternatives
p	Preference threshold
$P_j(a_1,a_2)$	Preference indicator
R	Sound reduction index [dB]
R-value	Thermal resistance [m^2·K·W^{-1}]
U-value	Thermal transmittance [W·m^{-2}·K^{-1}]
w_j	weight of criterion j
$\pi(a,b)$	Preference index
ϕ	Net outranking flow
ϕ^+	Positive outranking flow
ϕ^-	Negative outranking flow

Abbreviations:

EBX	Equibiaxial
EPP	Expanded polypropylene
EPS	Expanded polystyrene
EPS+GR	Expanded polystyrene with graphite particles
GFRP	Glass fiber reinforced plastic

ISO	International organization for standardization
FRP	Fiber-reinforced polymers
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LCEA	Life cycle energy analysis
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
MCDA	Multi-criteria decision analysis
PROMETHEE	Preference ranking organizational method for enrichment evaluation
PU	Polyurethane
XPS	Extruded polystyrene

2.1. Introduction

The construction industry plays a vital role in the world economy. This sector represents 25 % of the European industrial production and is estimated to account for 14.6 % of global gross domestic product by 2020 [1, 2]. Moreover, it is responsible for approximately one third of global carbon emissions [3]. The material selection of any construction is the most difficult and challenging step of any sustainable building project [4]. In the recent years, sustainability concept has grown and material selection takes into account not only physical-mechanical properties and technological requirements, but also economic, social and environmental issues. Consequently, in order to have a successful innovative product, sustainable requirements must be considered [5].

The energy consumption and CO_2 emissions are the two most considered indicators of sustainability in the construction industry [6]. Some EU countries (e.g. France) have already announced the will to reduce CO_2 emissions by 75 % before 2050 [7]. Also, some novel materials contribute to significantly reduce CO_2 emissions: González and Navarro [8] concluded that, by careful selection of low environmental impact materials, CO_2 emissions can be cut by up to 30 %; on the other hand, Goverse *et al.* [9] suggested that this number can reach ca. 50 %.

Advantages such as prompt construction, better quality, reduced need of resources and less waste have led to an increase in pre-fabricated housing [10]. There is also a growing interest in the use of composite wall systems in prefabrication industry due to lower environmental impact, light weight and lower energy consumption [11]. In addition to the environmental characteristics of these materials, one must also consider other requirements such as mechanical and thermal properties, acoustic performance, durability in specific environments, weight and dimension limits, safety, aesthetic considerations and cost [12]. Therefore, this paper adds environment to the typical design, product and cost selection criteria and proposes a combined material selection method for novel solutions for prefabricated housing [13]. Towards this end five advanced composite structures were studied concerning mechanical, thermal, acoustic, fire safety, cost and environmental aspects and compared to find the best solution. A multi-criteria decision analysis (MCDA) method PROMETHEE II (preference ranking organizational method for enrichment evaluation) was used to identify the best alternative. At end, the proposed solution was compared with a typical brick house considering technical requirements and midpoint and endpoint environmental impacts.

2.2 Literature review

Numerous studies exist on material selection towards a sustainable construction. However, most have not taken into account all three dimensions of sustainability, i.e. environment, economy and society. Berardi [14] remarkably points out the distinction between green and sustainable buildings; green buildings aim at minimizing environmental impact while sustainable building considers economic and social requirements as well.

Life cycle assessment (LCA), structured by international organization for standardization (ISO) 14040 series, is one of the most important tools to quantify environmental impacts of products through their life cycle and has been used in the building sector since 1990. According to ISO 14040 on the LCA framework, there are four following phases for any study: 1) Goal and scope definition; 2) life cycle inventory analysis (LCI); 3) life cycle impact assessment (LCIA); and 4) interpretation [15, 16]. Moreover, system boundaries define which of three phases of 1) construction, use and end-of-life to include in LCA study of buildings. Accordingly, approaches such as life cycle energy analysis (LCEA) and life cycle cost analysis (LCCA) have been used by numerous researchers to assess sustainability of buildings [17].

Quantifying gas emissions, and in particular CO_2, and embodied energy are two main methods that have been used by several LCA studies to assess environmental impacts of buildings. Some studies such as by González and Navarro [8] and by Goverse *et al.* [9] have estimated the environmental impacts evaluating solely CO_2 emissions. Moreover, Dimoudi and Tompa [18] considered SO_2 in addition to CO_2. Abeysundra *et al*. [19] have identified three factors of global warming potential, acidification potential and nutrient enrichment potential as main factors impacting the environment and calculated them based on CO_2 and NO_x emissions. Furthermore, Abeysundra *et al*. [20] have selected CO_2, SO_2 and PO_4 to estimate environmental impacts.

Several reports address the embodied energy in building materials. For instance, Reddy and Jagadish [21] studied the common materials used in buildings and compared them based on embodied energy. The studies which assess environmental impacts of buildings in terms of embodied energy can be categorized into two groups of 1) studies that assess contribution of different parts of buildings (e.g. roof, walls, etc.) such as by Dimoudi and Tompa [18], by Reddy and Jagadish [21] and by Thormark [22] and 2) studies that highlight involvement of the different phases of life cycle of building (e.g. manufacturing, recycling, etc.) as studied by Saghafi and Teshnizi [4], by Thormark [22], by Karimpour *et al.* [23] and by Vefago and Avellaneda [24]. Together, these studies outline that depending on the scope of study, single or multiple midpoints and endpoints can be used to evaluate environmental impacts of buildings. This variety of indicators makes the comparison of different studies very difficult. Therefore, it is suggested that future studies convert the environmental impacts into a common indicator such as equivalent CO_2 emissions to allow better comparison.

Berardi [14] claims that the social aspect is the most ignored dimension of sustainability. In recent years, several reports stress the importance of social factors in the selection of materials for the construction industry. Studies, such as by Franzoni [12] and by Ljungberg [25], have introduced social factors that must be taken into consideration. Florez and Castro-Lacouture [26] have proposed a mixed optimization model that considers features such as user appeal, functionality and resourcefulness as sustainability dimensions in addition to main technical factors. Normally, social analysis is being performed using questionnaires and personal interviews with individuals, as performed by Abeysundra *et al.* [19, 20], Florez and Castro-Lacouture [26] and Utama and Gheewala [27]. Holopainen *et al.* [28] point out that from a social perspective, high or low indoor temperatures are main causes of discomfort or distress for the occupants.

Reviewing these studies, one of the major drawbacks of studies on sustainable buildings is that as technological-oriented studies normally lack social inspiration, the social-oriented studies also need to integrate more technical requirements. However, before criticizing lack of social factors, one point that must be noted is the importance of system boundaries and scope of study. There seems to be no compelling reason to argue that LCA studies evaluating manufacturing and end-of-life phases must include as much social factors as those studying use phase.

2.3. Experimental material characteristics assessment

The increasing growth of composites in all industries has influenced the construction industry as well. Over the last decade there has been a significant growth in the use of fiber-reinforced polymers (FRP) in structural engineering [29]. The most common form in which FRP materials are used in constructions is called laminate consisting in a polymer resin reinforced with fiber (e.g. glass, carbon etc.) [30]. In order to obtain the required thickness and increase the bending stiffness, structural concept is used based on a combination of two laminates with a light core between known as sandwich panel or structural insulated panel. This sandwich-structured composite has various advantages such as long-term durability, a high strength to weight ratio, outstanding impact energy absorption and good temperature insulation [30]. In this study, a composite sandwich panel comprising two glass fiber-reinforced laminates sandwiching a polymer core is proposed for novel housing solution.

Glass fibers, as the most common reinforcing fibers for polymer matrix composites, have various benefits such as low cost, high tensile strength, high chemical resistance and excellent insulating properties [30]. The equibiaxial (EBX) woven roving of fiberglass with ±45º orientation was chosen as reinforcement examining two different combinations of EBX 700 $g \cdot m^{-2}$ and EBX 800 $g \cdot m^{-2}$. Epoxy and polyester are two main alternative resins for fiber-reinforced polymers in structural engineering. However, epoxy resins are preferred due to their adhesive properties, low shrinkage and environmental durability [29]. Also, Pihtili [31] has compared these two resins in fiber-reinforced polyester composite materials and concluded that epoxy has higher wear resistance compared with polyester. Therefore, epoxy was selected as resin for the composite sandwich panels. Mechanical tests were performed to assess the stability of matrix and reinforcement.

Thermal resistance, water absorption, mechanical properties, density and cost are main factors in selecting the core of panels [32]. Considering these factors, five polymers foams (i.e. polyurethane (PU 55), expanded polystyrene (EPS 150), expanded polystyrene with graphite particles (EPS+GR 30), extruded polystyrene (XPS 30) and expanded polypropylene (EPP 60)) were selected. All tested cores were 80 mm thick and the numbers after abbreviations refer to hardness or compressive strength of the material in different units depending on utilized standard by manufacturer.

2.3.1 Mechanical tests

To assess mechanical properties of the proposed sandwich panel, tensile and compression tests were carried out. The tensile tests were performed for two types of laminates: 1) 700 $g \cdot m^{-2}$ glass fiber reinforced plastic (GFRP); and 2) 800 $g \cdot m^{-2}$ GFRP. To perform the tests based on standard ISO 527-4, an Instron 4507 universal testing machine was used with a load cell of 300 kN and feed rate of 2 $mm \cdot min^{-1}$ at room temperature. To insure statistical relevance, five samples of each alternative (in total 10 samples) with dimension of 250 x 250 mm^2 and thickness of 2 mm or above were tested. The distance between grips was set to 150 mm.

To examine the compressive strength of five selected polymer cores, tests were performed in accordance with standards ASTM C 364-99 using an Instron 4208 universal testing machine. Maximum loads of 300 kN and the feed rate of 0.50 $mm \cdot min^{-1}$ were set and experiments run at room temperature. The samples were supported by a steel substrate in order to avoid overall bending. Five samples of each material were tested (in a total of 25 samples) and the average result recorded.

2.3.2 Fire performance tests

Fire performance of the materials in construction industry is of vital importance. The tests were performed according to standard ISO11925-2. A balanced - equibiaxial or EBX - woven roving of fiberglass and five alternative cores of PU, EPS, EPS+GR, XPS and EPP were examined to assess their fire safety performance. Fig. 2.1 shows the flame chamber machine (Atlas HVUL2 horizontal/vertical) where the tests were performed.

Fig. 2.1. Flame chamber machine where the fire tests were performed

2.3.3 Thermal and acoustic properties

Thermal conductivity coefficient is the primary property in thermal insulation selection [33, 34, 35, 36, 37]. However, there are factors such as density, age, operating temperature and material moisture content playing role in value of thermal conductivity [34, 35, 37, 38]. Moreover, there are factors such as thermal capacity, thermal reflectivity, emissivity and thermal bridging that affect thermal behavior of building [38, 39, 40]. Therefore, in order to understand thermal behavior of building thoroughly, in-door operative temperature and surface temperature need to be inspected through time. Materials with low thermal conductivity have low thermal transmittance (*U-value*) and high thermal resistance (*R-value*) and consequently are suitable for thermal insulation [33]. The thermal conductivity of each alternative core at room temperature was provided by the corresponding manufacturer. By having the thermal conductivity and thickness, thermal resistance (*R-value*) of each core was calculated and compared.

As noise coming from outside a building or from adjacent spaces within a building may be uncomfortable to its occupants, the acoustic characterization of building materials should be taken into consideration [41]. The sound reduction index *R*, which determines the capacity of material to absorb the sound, was used to compare alternatives. Materials with higher sound reduction index have higher capacity to absorb the sound and, consequently, are better sound insulators. Sound reduction index [dB] was calculated based on mass law for acoustic insulation, Eq. (2.1) [42]:

$$R = 20 \cdot \log (m_s \cdot f) - 47.3 \qquad (2.1)$$

where f is the frequency [Hz], which was set at 500 Hz, m_s is the mass per unit area of the panel [$kg \cdot m^{-2}$] for each alternative and 47.3 is a numerical constant.

2.3.4 Environmental impacts

Considering the four steps of LCA that were mentioned before, and that the goal of this study is to assess environmental impacts associated with novel housing materials, the scope is limited to the manufacturing phase and does not include the operational phase and use energy. Furthermore, due to different density of alternative materials in such comparisons, Tabone *et al*. [43] recommended using the volume instead of mass as functional unit. Therefore, the functional unit of comparison was set to 0.082 m^3 of each alternative (1 m^2 surface of wall multiplied by 0.082 m thickness of wall). To perform the LCI and LCIA, Software *SimaPro ver. 7* was used. Within this software, *IDEMAT 2001* was selected as the database, to collect the required data for LCI, and *ReCiPe Endpoint (H) ver. 1.11 / Europe ReCiPe H/A* was applied as calculation method. The ReCiPe is one of the most recent and harmonized indicator approaches available in LCIA [44, 45]. This methodology combines two widely used LCIA methods: 1) *CML* (midpoint-oriented) and 2) *Eco-indicator 99* (endpoint-oriented) by converting inventory parameters firstly into eighteen midpoint indicators and then three endpoint damage categories. Midpoint indicators facilitate differentiating between various impact categories and endpoint indicators simplify comparing total damage. At the end, by assigning weights to three endpoint damage categories of human health, ecosystems and resources, a single score representing total environmental impact is calculated. Values for normalization and weighting vary depending on selected version of the software. There are two references of *Europe* and *World* advising different normalization factors. Furthermore, the study timeframe depends on the selection of three perspectives: 1) individualist (I) in favor of short-time interest; 2) egalitarian (E) as the most precautionary perspective; and 3) hierarchist (H) based on the most common policy principles. The used calculation method for this study was *ReCiPe Endpoint (H) ver. 1.11 / Europe ReCiPe H/A* which refers to hierarchist perspective and normalization values of Europe with the average weighting set recommended by the methodology as shown in Table 2.1[46].

Table 2.1. Normalization and weighting factors recommended by *Europe ReCiPe H/A* methodology [46]

Damage category	Normalization factor	Weight
Human health	49.5	400
Ecosystems	5530	400
Resources	0.00324	200

2.3.5 Cost analysis

Cost, as one of the main dimension of sustainability, must be considered in material selection of the proposed sandwich panel. Cost of the panel including costs of core, resin, fiber and assembling were estimated for each alternative. The estimated cost was not limited to various local suppliers, but also average international cost that was calculated using available data in software application *CES EduPack*.

2.4. Results and discussion

2.4.1 Mechanical tests

Table 2.2 presents the results of the tensile tests performed in the EBX proposed laminates. The table shows glass fiber properties as well as those of the selected epoxy resin (CR 83-2). The results show no clear difference between young's modulus and tensile strength of EBX 700 $g{\cdot}m^{-2}$ and EBX 800 $g{\cdot}m^{-2}$. The compression results are presented in the Table 2.3; EPP showed the best performance with a compressive strength of 1.3 MPa and appropriate compatibility with the laminate. EPS+GR proved to be the best core with the best adhesion to laminate where adhesion is indicated by laminate-core delamination in test. However, the compressive strength is poor compared with the other alternatives.

Table 2.2. Mechanical properties of selected laminates

Sample	young's Modulus [GPa]	Tensile Strength [MPa]
Raw Materials		
Epoxy resin CR83-2	2.96	84
Glass fiber	73	3400
Laminate (at 0º orientation)		
EBX700	8.69	100.1
EBX800	8.96	103.0

Table 2.3. Mechanical properties of selected sandwich panels

Sample		Compressive Strength-Core [kPa]	Compressive Strength [kPa]	Delamination Laminate-Core
PU 55	EBX700	320	1048.75	95 %
	EBX800	320	1305.91	100 %
EPS 150	EBX700	150	1201.60	50 %
	EBX800	150	967.91	32 %
EPS+GR 30	EBX700	60	714.90	0 %
	EBX800	60	865.38	24 %
XPS 30	EBX700	300	1031.38	56 %
	EBX800	300	1213.38	100 %
EPP 60	EBX700	400	1331.26	30 %
	EBX800	400	1352.81	48 %

2.4.2 Fire performance tests

Results of flammability tests are shown in Fig. 2.2. In it, the flammability of selected materials including laminates and five proposed polymer cores is compared. The samples were classified from A to F, where A (fireproof/non-combustible) is the best and F is the worst (must not be used for civil applications in Europe). Although cores PU, EPS+GR and XPS are all classified as E, PU showed better fire performance followed by XPS and EPS+GR. The other cores, as well as laminate EBX were classified as F implying poor fire safety performance.

Sample	EBX	PU 55	EPS 150	EPS + GR 30	XPS 30	EPP 60
Euroclass	F	E	F	E	E	F

Fig. 2.2. Results of fire performance tests of selected materials

2.4.3 Thermal and acoustic properties

Table 2.4 compares thermal resistance (*R-value*) and sound reduction index of selected core materials at thickness of 80 mm.

Table 2.4. Thermal and acoustic properties of selected core materials

Core	Thermal resistance $[m^2 \cdot K \cdot W^{-1}]$	Sound reduction index [dB]
PU 55	4	18.79
EPS 150	2.29	12.38
EPS+GR30	2.50	17.47
XPS 30	2.22	17.47
EPP 60	1.90	21.44

2.4.4. Environmental impacts

Environmental impacts of alternative core materials quantified by total endpoint single score are shown in Fig. 2.3. EPP shows the highest ReCiPe point of 2.64, followed by PU with 1.85, XPS with 1.65, EPS+GR with 1.33 and EPS with the lowest environmental impact of 0.74.

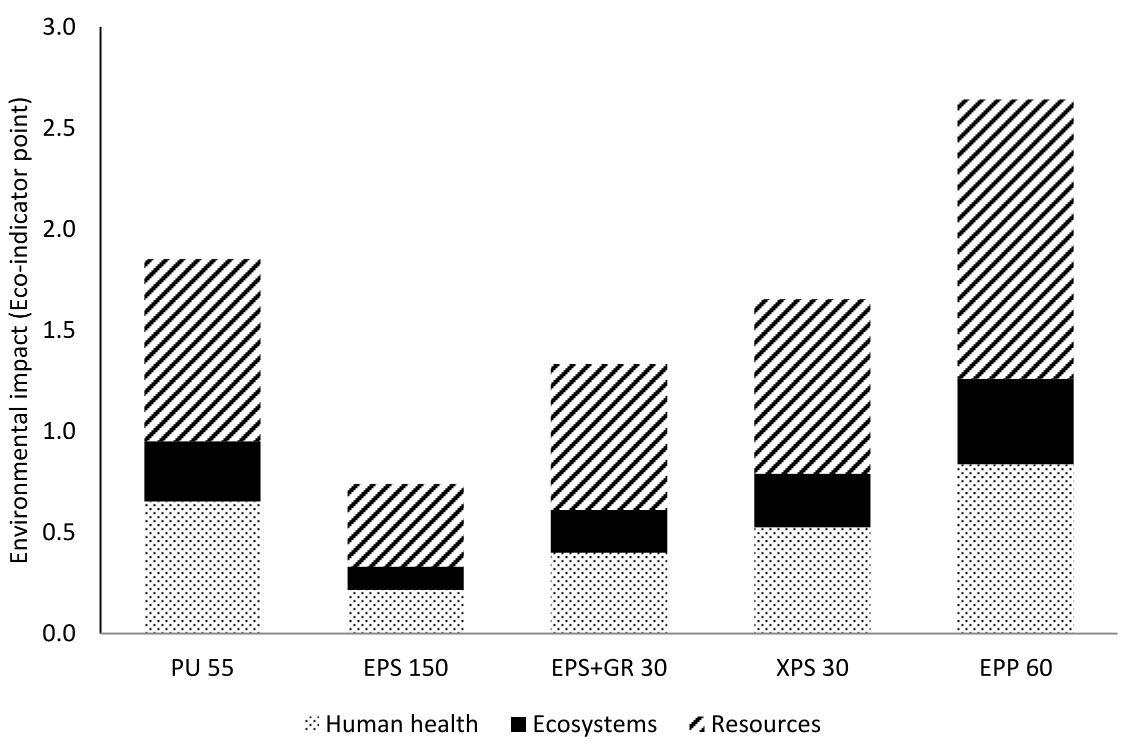

Fig. 2.3. Endpoint environmental impact of selected core materials

2.4.5 Cost analysis

Table 2.5 compares the estimated cost of selected core materials and Table 2.6 shows the estimated cost for the resin and fiber materials. Specific glass fibre cost is constant (as per Table 2.6). Nonetheless, please note that higher mass reinforcements are proportionally more expensive and that any variation in specific glass fibre cost only reflects manufacturing differences.

Table 2.5. Estimated cost of selected core materials

Core	Estimated cost [€·m^{-2}]
PU 55	21.9
EPS 150	4.2
EPS+GR 30	7.5
XPS 30	7.5
EPP 60	9.5

Table 2.6. Estimated cost of resin and fiber materials

Material	Estimated cost [€·kg^{-1}]
Resin	
Epoxy	6.90
Polyester	1.81
Fiber	
EBX 300 g·m^{-2}	3.70
EBX 400 g·m^{-2}	3.70
EBX 600 g·m^{-2}	3.70

2.4.6 Decision Making

For selected fiber materials, the tensile strength, young's modulus and cost are very similar. The EBX fabric with two layers of reinforcement (one 300 g·m^{-2} and one 400 g·m^{-2} giving 700 g·m^{-2}) was selected due to tensile strength requirements to be used as reinforcement of the epoxy resin. Table 2.7 summarizes the properties for selected core materials in combination with laminate of EBX 700 g·m^{-2}. Moreover, decision making radar chart is presented in Fig. 2.4 for better comparison of different alternatives.

Table 2.7. Properties of selected core materials

Core	Compressive Strength [kPa]	Delamination Laminate-Core	Density [kg·m^{-3}]	Fire Euroclass	Thermal resistance [m^2·K·W^{-1}]	Sound reduction index [dB]	Environmental impact [ReCiPe point]	Cost [€·m^{-2}]
PU 55	1048.8	95 %	50.4	E	4	18.79	1.85	41.5
EPS 150	1201.6	50 %	24.1	F	2.29	12.38	0.74	23.9
EPS+GR30	714.9	0 %	43.3	E	2.50	17.47	1.33	27.2
XPS 30	1031.4	56 %	43.3	E	2.22	17.47	1.65	27.2
EPP 60	1331.3	30 %	68.4	F	1.90	21.44	2.64	29.1

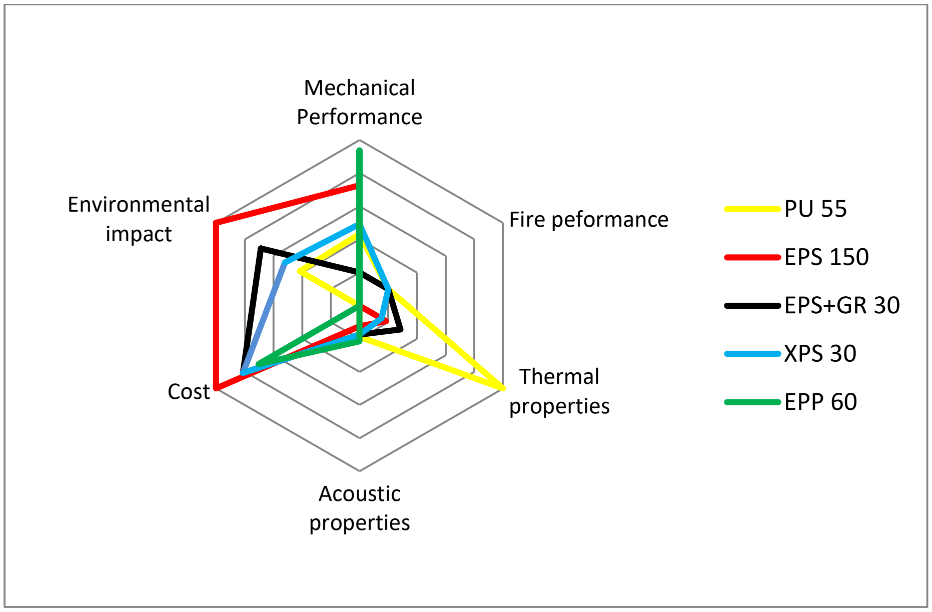

Fig. 2.4. Decision making radar chart for core material selection

In recent years numerous multi-criteria decision analysis (MCDA) techniques have been developed to help in selecting the best alternative concerning different criteria. PROMETHEE is an outranking approach based on pair-wise comparison of alternatives and one of the most accepted and widely used MCDA methods [47, 48, 49, 50]. While PROMOTHEE I provides partial ranking, PROMOTHEE II offers full ranking of alternatives. Therefore, regarding the purpose of this study, PROMOTHEE II was used for comparison of alternatives. This method firstly sets N number of alternatives $\mathbf{A}=[a_1,a_2,\ldots,a_N]$ to be evaluated in terms of M number of criteria $\mathbf{C}=[c_1,c_2,\ldots,c_M]$. Then it defines $g_j(a_j)$ as value of alternative a_j for criterion c_j and consequently Eq. (2.2) calculates $d_j(a_1,a_2)$ as deviation between values of alternatives a_1 and a_2 [50]. Considering the deviation, the decision maker assigns a preference to the best alternative between 0 and 1 where 0 indicates no preference or indifference and 1 signifies outright preference. This preference indicator is defined as $P_j(a_1,a_2)$ and compares each pair of alternatives on that particular as presented in Eq. 2.3 [48].

$$d_j\left(a_1,a_2\right)=g_j\left(a_1\right)-g_j\left(a_2\right) \qquad (2.2)$$

$$P_j\left(a_1,a_2\right)=\mathrm{F}_j\left[d_j\left(a_1,a_2\right)\right] \qquad (2.3)$$

There are different preference functions for pairwise comparison of alternatives. The method recommends V-shape preference function for quantitative and usual for qualitative criteria that are respectively calculated by Eqs. (2.4) and (2.5) [51, 52]. Hence, usual preference function was used for the fire performance as qualitative criterion and V-shape for rest of criteria which are all quantitative. Preference threshold p is the smallest deviation which is considerable as adequate to conclude a full preference.

$$\text{Usual preference function } \mathrm{F}_j(d_j) = \begin{cases} 0 & \text{if } d_j \le 0 \\ 1 & \text{if } d_j > 0 \end{cases} \qquad (2.4)$$

$$\text{V-shape preference function } \mathrm{F}_j(d_j) = \begin{cases} 0 & \text{if } d_j \le 0 \\ \dfrac{d_j}{p} & \text{if } 0 \le d_j \le p \\ 1 & \text{if } d_j > p \end{cases} \qquad (2.5)$$

From this, decision makers define non-negative number of w_j as weight of criterion j in accordance to importance of that criterion. Therefore, preference index is denoted as $\pi\,(a,b)$ and is calculated by Eq. (2.6) [48].

$$\pi\left(a_1,a_2\right)=\frac{\sum_{j=1}^{M}P_j\left(a_1,a_2\right)w_j}{\sum_{j=1}^{M}w_j} \qquad (2.6)$$

Considering positive outranking flow as defined as $\phi^+(a)$, which is calculated by Eq. (2.7), and negative outranking flow as $\phi^-(a)$, which is calculated by Eq. (2.8) [50].

$$\varphi^+\left(a\right)=\frac{1}{N-1}\sum_{x\in A}\pi\left(a,x\right) \qquad (2.7)$$

$$\varphi^-\left(a\right)=\frac{1}{N-1}\sum_{x\in A}\pi\left(x,a\right) \qquad (2.8)$$

Finally, PROMOTHEE II completes the ranking by defining net outranking flow as $\phi(a)$, which is calculated by Eq. (2.9) [48]. The alternative with the highest value of $\phi(a)$ is the best possible choice [49].

$$\phi(a) = \phi^{+}(a) - \phi^{-}(a) \qquad (2.9)$$

Defining weights is a vital step in any MCDA method that must be accomplished by the decision makers [50]. Considering different aspects of this study, the weightings assigned for each factor were 3 for compressive strength, thermal properties, fire performance and acoustic properties, 5 for environmental impact and cost, as dimensions of sustainability, and 1 for laminate-core delamination. The preference threshold p was set to range (difference between maximum and minimum) of values of alternatives for each criterion to obtain a fully linear preference function. The assigned weights and preference factors for all criteria are shown in Table 2.8.

Table 2.8. Selected Preference factors for PROMETHEE II analysis

Preference	Compressive Strength	Delamination Laminate-Core	Fire Euroclass	Thermal resistance	Sound reduction index	Environmental impact	Cost
Min/Max	Max	Min	A	Max	Max	Min	Min
Weight	3	1	3	3	3	5	5
Preference Function	V-shape	V-shape	Usual	V-shape	V-shape	V-shape	V-shape
Preference threshold	616.4	95	n/a	2.1	9.06	1.90	17.6

By inputting values from Table 2.7 and Table 2.8 and using Software *Visual PROMETHEE ver. Academic*, the PROMETHEE II analysis was performed which led to the ranking shown in Table 2.9.

Table 2.9. Ranking of selected materials based on PROMETHEE II analysis

Core	ϕ	Rank
XPS 30	0.0659	1
EPS+GR 30	0.0503	2
EPS 150	0.0429	3
PU 55	-0.0171	4
EPP 60	-0.1419	5

2.4.7 Discussion

Due to high cost, PU did not seem a suitable core material although having high thermal resistance. EPP is a good alternative when mechanical and acoustic properties are required, but it has a high environmental impact. EPS+GR did not fulfill the mechanical requirements in spite of no delamination. EPS proved to be the most environmentally friendly option, though presents high flammability and acoustic properties. Considering all properties, XPS shows the best balance as core material in sandwich panel.

In order to further compare how XPS 30 core composite sandwich panel can be considered a possible housing solution, this structure was compared with a typical masonry building in order to gain insights into benefits and drawbacks. The masonry building was assumed to be composed of a brick wall structure based on standard Eurocode 6 BS EN 1996. The selected brick type was a typical Italian standard hollow brick with dimensions of 500 x 189 x 150 mm^3. The mortar M5 (Type N, traditional mix II) was selected in accordance to standard BS EN 998 with 10 mm thickness between the brick layers and 15 mm thickness on both internal and external surfaces of the wall. Fig. A2 and Table A1 provide more details about components of brick wall structure. The mechanical, thermal, acoustic and fire performance of the brick wall were calculated according to Eurocode standards. A functional unit of 1 m^2 of the proposed sandwich panel was compared with the brick wall concerning mechanical, thermal, acoustic, fire safety and environmental aspects. The results of this comparison are set out in Table 2.10. More details of calculations are presented in appendix A.

Table 2.10. Properties of the proposed sandwich panel solution compared with a typical brick wall

Property	XPS core sandwich panel	Brick wall	Unit
Compressive Strength	1031	4153	[kPa]
Specific strength	18418	4223	[$N \cdot m \cdot kg^{-1}$]
Euroclass fire properties	E	A1	
Density	66	983	[$kg \cdot m^{-3}$]
Thermal resistance	2.23	1.25	[$m^2 \cdot K \cdot W^{-1}$]
Sound reduction index	19.92	51.64	[dB]
Environmental impact	0.65	1.50	[ReCiPe point]

Concerning environmental impact, Software *SimaPro ver. 7* was used with *IDEMAT 2001* database and *ReCiPe Endpoint (H) ver. 1.11 / Europe ReCiPe H/A* impact assessment calculation method. Table. 2.11 compares the environmental impacts of these two structures at three endpoint damage categories of human health, ecosystems and resources. The results highlight advantage of the proposed sandwich panel in terms of environmental impacts at all endpoint damage categories in comparison with brick wall.

Table 2.11. Endpoint environmental impacts of XPS core sandwich panel and brick wall

Damage category	XPS core sandwich panel	Brick wall	Unit
Human health	0.436	0.980	[ReCiPe point]
Ecosystems	0.213	0.524	[ReCiPe point]
Resources	0.0000337	0.0002986	[ReCiPe point]
Total	0.6495338	1.5044657	[ReCiPe point]

In accordance to ISO 14042 and in order to gain insights into environmental impacts of both scenarios more specifically, characterization of midpoint indicators was calculated by using Software *SimaPro ver. 7* with *IDEMAT 2001* database and *ReCiPe Midpoint (H) ver. 1.11 / Europe ReCiPe H* impact assessment calculation method. The midpoint indicators with value zero were omitted and other midpoints were converted to relative scale ranging from 0 to 100 % for better comparison of two scenarios. Fig. 2.5 compares environmental impacts of the proposed sandwich panel with a typical masonry building at various impact categories. These results point out excellence of the proposed panel in fourteen out of fifteen midpoint categories.

As mentioned in the literature review, there are many former studies that have presented environmental impacts in terms of CO_2 emissions. Thus, by using midpoint indicators and impact category of climate change, the equivalent CO_2 emissions for both scenarios were calculated. Software *SimaPro ver. 7* with *IDEMAT 2001* database was used and to avoid uncertainties associated with different methods, various impact assessment calculation methods were applied. The results of these calculations are set out in Table 2.12.

Table 2.12. Equivalent CO_2 emissions of XPS core sandwich panel and brick wall

Impact assessment calculation method	XPS core sandwich panel	Brick wall	Unit of equivalent CO_2
ReCiPe Midpoint (H) ver. 1.11	11.6	28.9	[kg]
ReCiPe Midpoint (I) ver. 1.11	13.4	29.1	[kg]
ReCiPe Midpoint (E) ver. 1.11	10.9	28.8	[kg]
EDIP 2003 ver. 1.01	11.6	29.1	[kg]
CML 2001 ver. 2.04	11.5	29.1	[kg]
IMPACT 2002+ ver. 2.05	10.9	29	[kg]
Average	11.65	29	[kg]

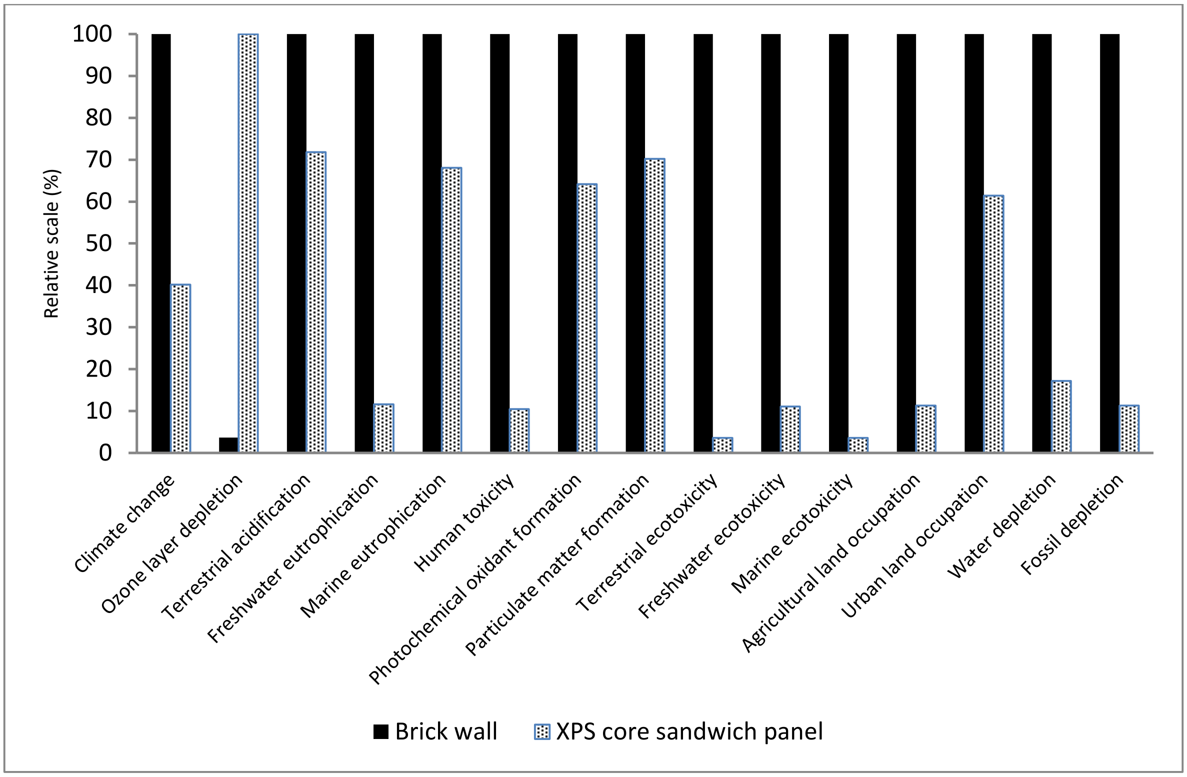

Fig. 2.5. Midpoint environmental impacts of XPS core sandwich panel and brick wall

2.5. Conclusions

This article discusses advanced sandwich-structured composites for prefabricated housing. Five alternative sandwich panel structures were studied concerning mechanical, thermal, acoustic, fire safety, cost and environmental properties. Based on PROMOTHEE II multi-criteria decision analysis, sandwich panel consisting of XPS core and glass fiber laminate were selected as the optimal solution. The proposed structure was further compared with brick masonry aiming highlighting the benefits and drawbacks of composites as construction materials.

Results point out that although the proposed sandwich panel has lower compressive strength it has a considerably higher specific strength compared with the brick wall. Moreover, having only 7 % of the density of a brick wall is a key advantage of composite sandwich panel in prefabrication industry where low weight materials are needed. The proposed panel has 1.8 times better thermal resistance compared with the brick wall. Furthermore, given the low thermal conductivity of foam core, even better thermal insulation can be obtained by increasing thickness of the wall. Acoustic and fire properties are two areas where brick walls perform better than the proposed panel. Adding surface coatings may be a possible solution to improve these two properties of the proposed panel.

The comparison of environmental impacts shows that the resulting sandwich panel has less environmental impact than the brick wall, highlighting 57 % less total environmental impact. Converting environmental impacts into equivalent CO_2 emissions, the sandwich panel presented 60 % less CO_2 emissions. From the endpoint indicators, it was shown that the proposed panel has 89 % less environmental impact in terms of resources, 55 % less concerning human health and 59 % in the matter of ecosystem quality. Moreover, assessment of midpoint impact categories proved that the suggested structure has significantly lower environmental impacts in urban land occupation, agricultural land occupation, marine ecotoxicity, marine eutrophication, freshwater ecotoxicity, freshwater eutrophication, terrestrial acidification, terrestrial ecotoxicity, particulate matter formation, photochemical oxidant formation, human toxicity, water depletion, fossil depletion and climate change and only shows higher impacts concerning ozone layer depletion. A possible explanation of high impact of the proposed panel on ozone layer depletion might be due to existence of ozone depleting substances such as hydrochlorofluorocarbon (HCFC) in extruded polystyrene. Nevertheless, global trends to phase out HCFC use and current attempts aiming at developing zero ozone depleting foaming agent technologies for extruded polystyrene would decrease environmental impact of the proposed panel.

While former studies on using composite sandwich panel in buildings have mainly focused on thermal properties, density and cost, this research evaluates other factors such as acoustic, mechanical and fire properties of different sandwich panel structures. Moreover, while using a single endpoint indicator of environmental impacts was sufficient for the multi-criteria decision analysis, sustainability of the structure was compared at various midpoint and endpoint impact categories to aid possible future solutions aiming at reducing environmental impact of composite sandwich panels. Furthermore, applying and comparing different impact assessment methods for identifying equivalent CO_2 emissions provides higher reliability of results.

Acknowledgement

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Appendix A

Overall thermal resistance of wall was calculated by summing thermal resistance of components in series or parallel form, as appropriate, considering one-dimensional steady-state heat conduction though plane wall. Thermal conductivity, density and fire performance of components were provided by the manufacturer. By having density, sound reduction index was calculated according to Eq. (2.1).

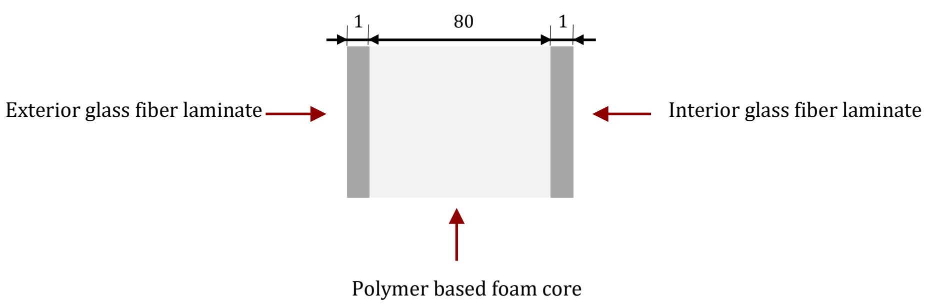
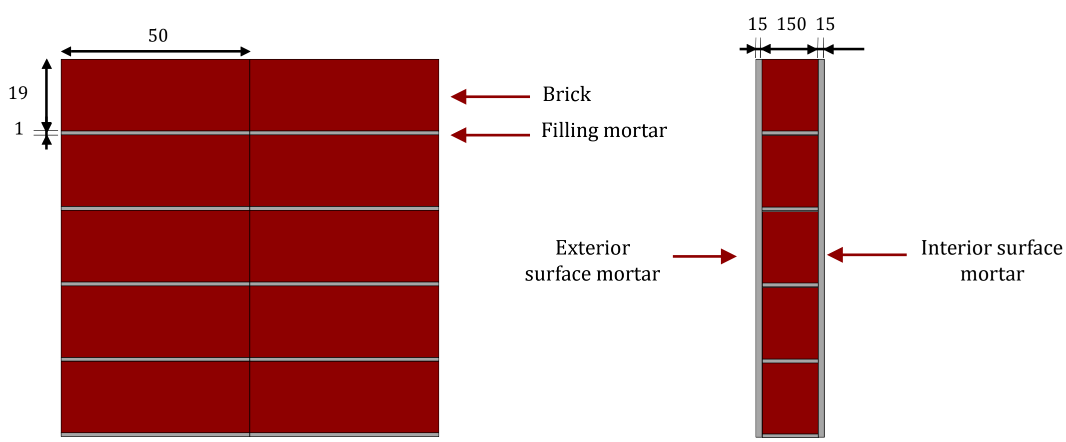


Fig. A1. Proposed panel design comprehending two glass fiber laminates sandwiching a polymer based foam core (all dimensions are in mm)



a) Elevation view b) section view

Fig. A2. a) Elevation and b) Section views of brick wall structure (all dimensions are in mm)

Table A1. Thermal properties of components of brick and composite walls

Construction	Layer	Thickness [m]	Density [kg·m^{-3}]	Thermal conductivity [W·m^{-1}·K^{-1}]	R-value [m^2·K·W^{-1}]
Brick wall		0.18	983	0.14	1.25
	Exterior surface mortar	0.015	1800	0.9	0.02
	Brick	0.15	800	0.82	0.19
	Filling mortar	0.15	1800	0.9	3.33
	Interior surface mortar	0.015	1500	0.9	0.02
Composite wall		0.082	66	0.037	2.23
	Exterior glass fiber laminate	0.001	1850	0.42	0.002
	XPS 30 foam core	0.080	43.3	0.036	2.22
	Interior glass fiber laminate	0.001	1850	0.42	0.002

Regarding mechanical properties, the compressive strength of the brick wall structure with general purpose mortar was calculated according to the standard Eurocode 6 BS EN 1996, Eq. (A1):

$$f_k = K \cdot f_b^{0.7} \cdot f_m^{0.3} \qquad \text{(A1)}$$

in which f_k is the characteristics compressive strength of the masonry, f_b is the normalized mean compressive strength of units and f_m is the compressive strength of the mortar. The values of f_b and f_m were measured and declared by manufacturer in accordance to standards EN 772-1 and EN 998-2, respectively. Moreover, K is a constant that is being defined based on type of masonry unit and mortar according to the Table 3.3 of the standard Eurocode 6 BS EN 1996. Consequently, set values were 12 MPa for f_b, 5 MPa for f_m and 0.45 for K.

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CHAPTER 3 ENVIRONMENTAL IMPACT ASSESSMENT

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ABSTRACT

Recent worldwide concerns on environmental issues have led to a trend to reduce greenhouse gas emissions. Previous studies indicate that building sector is responsible for almost one third of global carbon emissions. Therefore, there is an urgent need to decrease these emissions not only in use phase, but also by substituting typical construction materials with novel green alternatives. Quite recently, considerable attention has been paid to composites as construction materials. This paper proposes a sandwich-structured composite as building material. The proposed structure is evaluated in terms of environmental impact in comparison with a typical masonry structure through a life cycle assessment. The two structures have being studied based on a one-storey house. *Eco-indicator 99 H/A* impact assessment method was applied to transform the environmental impacts in three damage categories at human health, ecosystem quality and resources. The results show that the environmental impact of the proposed structure is reduced by 43 % when in compared with a typical masonry structure.

Keywords: Green building, Life cycle assessment, sandwich-structured composite, sandwich panel

3.1 Introduction

The growth of the sustainability concept driven by the acknowledgement of environmental limits, the need for lower CO_2 emissions etc. have implied that the building sector impact, that constitutes almost one third of global carbon emissions, was highlighted. Carbon emissions in this industry can be classified into embodied and operational emissions [1]. The proportions of embodied and operational emissions vary in different studies. Several studies have concluded operational emissions account for 70-80 % of emissions. On the other hand, there is also growing support for the idea that CO_2 emissions can be reduced significantly by selecting low environmental impact materials [1-3]: González and Navarro [4] suggest that up to 30 % carbon emissions can be cut while Goverse et al. [5] conclude that this number can almost reach 50 %.

Over the last decade there has been a notable development in the use of fiber-reinforced polymers as construction materials [6]. Laminates, constituted by a fibre reinforced polymer resin are the most typical form of composites in construction. Another composite alternative is a sandwich panel construction, consisting of two laminates enclosing a light core with several benefits such as long-term durability, a high strength to weight ratio, outstanding impact energy absorption, and good temperature insulation [7].

Life cycle assessment (LCA) has been developed as a tool to evaluate environmental impacts of different products. Building sector LCAs can be complex due to the long lifespan of buildings and shorter lifespan of some constituent elements [8]. The ISO 14040:2006 standard defines four assessment steps of 1) goal and scope definition, 2) inventory analysis, 3) impact assessment and 4) interpretation for any life cycle assessment. The first step defines the goal and system boundaries. The second step collects all input/output data to be used in third step, which converts them into environmental impacts. The last step is concerned with the interpretation of results [9].

The aim of this article is to assess sandwich-structured composite as novel green building material through life cycle assessment. Toward this end a composite sandwich panel comprising two glass-fiber reinforced laminates sandwiching an extruded polystyrene core is studied as a possible building material. The proposed structure was compared with a typical masonry building for a one-storey house in terms of CO_2 emissions.

3.2 Methodology

3.2.1 Goal and scope definition

In order to assess the proposed building material, two scenarios were studied based on a one-storey house: a sandwich-structured composite and a typical masonry system. The two scenarios are different in terms of building material and also supporting foundations. The functional unit of comparison is the whole building excluding doors and windows. The system boundary of this study is limited to materials that embody gas emissions and does not include operational emissions.

3.2.2 Building description

For the purpose of this work, a 30 m^2 one-storey house was considered for a single family as is shown in Fig. 3.1. The house includes a living room, one bedroom and one bathroom. There are four external and three internal walls with specified space to install doors and windows.

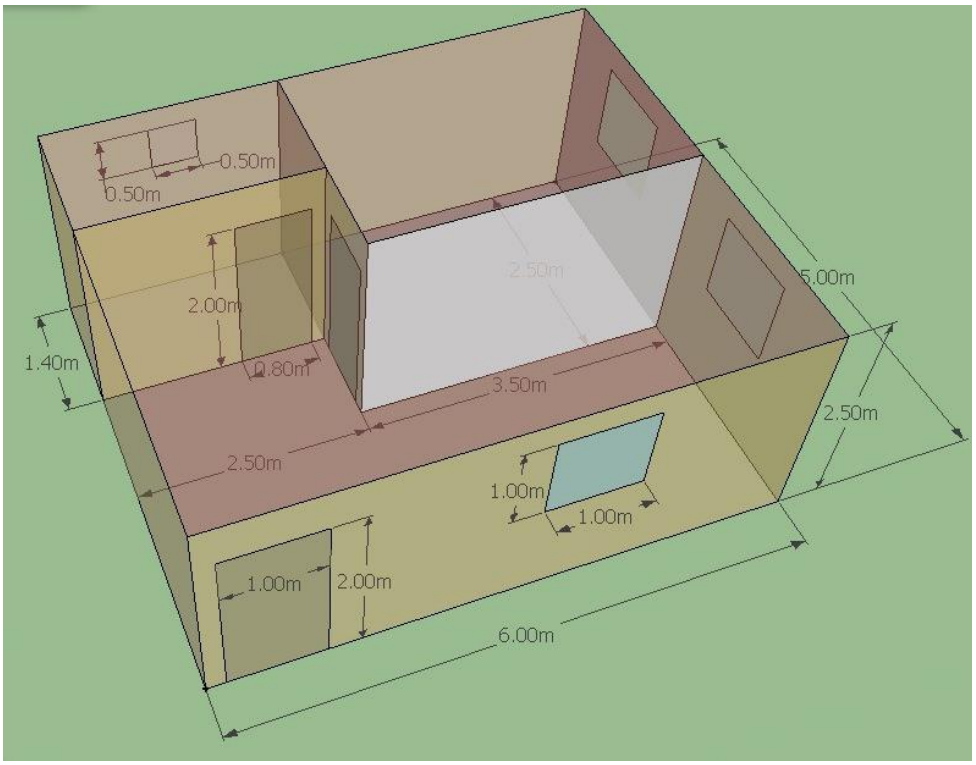

Fig. 3.1. Model of the studied building

3.2.3 Life Cycle Inventory analysis (LCI)

Based on the described model building, two construction material scenarios were defined: a sandwich-structured composite and a typical masonry system. Table 3.1 presents the inventory analysis of these two scenarios.

3.2.4 Scenario 1: Sandwich-structured composite

Sandwich-structured composite was proposed as novel material for the considered building. The proposed sandwich panel can be used for the walls, floor and roof. The panel consists of two glass-fiber reinforced laminates and a light core. The core material is extruded polystyrene and has thickness of 80 mm. Equibiaxial

(EBX) woven roving of fiberglass with ±45º orientation was chosen as reinforcement and epoxy resin was considered making the total thickness of the panel 82 mm. Mechanical, thermal, acoustic and fire performance tests were performed to assure the proposed panel has required properties to be used as building material. All four external and three internal walls, roof and floor are made of the proposed sandwich panel. Concerning the foundation, strip footing of reinforced concrete with width of 100 mm and height of 200 mm was considered. Epoxy glue with thickness of 15 mm connects panels together and also links the composite structure to the foundation.

3.2.5 Scenario 2: Typical masonry system

The typical masonry system scenario, considering a masonry structure composed of brick walls, is based on standard Eurocode 6 BS EN 1996. The selected brick considered was the typical Italian industry standard with dimension of 500 x 190 x 150 mm^3 for external walls and 500 x 190 x 80 mm^3 for internal walls. The roof is made of a pre-stressed reinforced concrete slab built in a reinforced concrete beam (180 x 200 mm^2) cast along the whole top contour of the external walls. The slab contains pre-stressed inverted T beams with 400 mm width per 120 mm height ceramic blocks in between. A 30 mm thick top layer of reinforced concrete completes the roof slab with a total thickness of 150 mm. The floor comprises a 200 mm thick layer of sand and gravel with equal proportions below a 150 mm thick layer of reinforced concrete. Regarding the foundation, strip footing of reinforced concrete with height of 200 mm and width of 200 mm for internal walls and 300 mm for external walls were considered. The mortar M5 (Type N, traditional mix II) was selected in accordance to standard BS EN 998 with 10 mm thickness between the brick layers, also between walls and foundation and similarly between external walls and top beam. The same mortar was used on both surfaces of walls with 10 mm thickness for internal walls and 15 mm for external walls resulting total thickness of 10 mm for internal walls and 15 mm for external walls.

Table 3.1. Inventory analysis of both scenarios

Part	Material	Volume [m^3]	Density [$kg{\cdot}m^{-3}$]	Mass [kg]
Scenario 1) Sandwich panel building				
Floor	Sandwich panel	2.46	66	162.36
Roof	Sandwich panel	2.46	66	162.36
External walls	Sandwich panel	4.079	66	269.25
Internal walls	Sandwich panel	1.48	66	97.69
Foundation	Reinforced concrete	0.61	2500	1525
Connections	Epoxy glue	0.146	1000	146.49
Scenario 2) Masonry building				
Floor	Sand	3	1600	4800
Floor	Gravel	3	1500	4500
Floor	Reinforced concrete	4.5	2500	11250
Roof	Ceramic blocks	2.769	400	1107.69
Roof	Reinforced concrete	0.831	960	797.54
Roof	Reinforced concrete	0.9	2500	2250
External walls	Brick	7.05	800	5640
External walls	Mortar	1.905	1800	3429
Internal walls	Brick	1.359	880	1195.92
Internal walls	Mortar	0.446	1800	802.8
Foundation	Reinforced concrete	1.66	2500	4150
Connections	Mortar	0.3396	1800	611.28

3.2.6 Life cycle impact assessment (LCIA)

There are multiple environmental impacts in any LCA study depending on utilized methods, characterizations and impact categories. The goal of LCIA is to aggregate inventory data into specific environmental impact classifications. The LCIA methods are classified into two groups of problem-oriented (mid-points) and damage-oriented (end-points). Although problem-oriented methods provide a more comprehensive picture of impacts, but interpretations of results would be challenging [8,10].

In order to perform the LCIA, Software *SimaPro ver. 7* was used with *IDEMAT 2001* as database and *Eco-indicator 99 H/A ver. 2.06* as impact assessment calculation method. This method transforms the environmental impacts in three damage categories at human health (consisting of climate change, ozone layer, radiation, respiratory organics and inorganics and carcinogens), ecosystem quality (including land use, acidification/eutrophication and ecotoxicity) and resources (comprising minerals and fossil fuels). At the end, the method assigns weights of 20 % to resources, 40 % to human health and 40 % to ecosystem to obtain a single score for total endpoint [11].

3.3 Results and Discussion

Fig. 3.2 compares the environmental impacts of two scenarios in three impact categories at human health, ecosystem quality and resources. The results show total endpoint single score of 960 for the masonry building while this number for sandwich-structured composite building is 414, meaning that the proposed structure presents only 43 % of masonry building's environmental impacts. The main environmental damage category of the proposed sandwich-structured building is "resources" with eco-indicator point of 308 while this number for masonry building is 159 (almost half). This damage category indicates surplus energy needed for future extractions of minerals and fossil fuels. On the other hand, composite building has eco-indicator point of 95.9 for damage category of "human health" which is only 13 % of the one for masonry building (714). The "human health" includes the number and duration of disease, and life years lost because of permanent death from environmental causes. At end, the eco-indicator point for damage category of ecosystem quality is 9.91 that is only 11 % of the one for the masonry building (87). The "ecosystem quality" implies loss of species over a certain area, during a certain time due to use of materials.

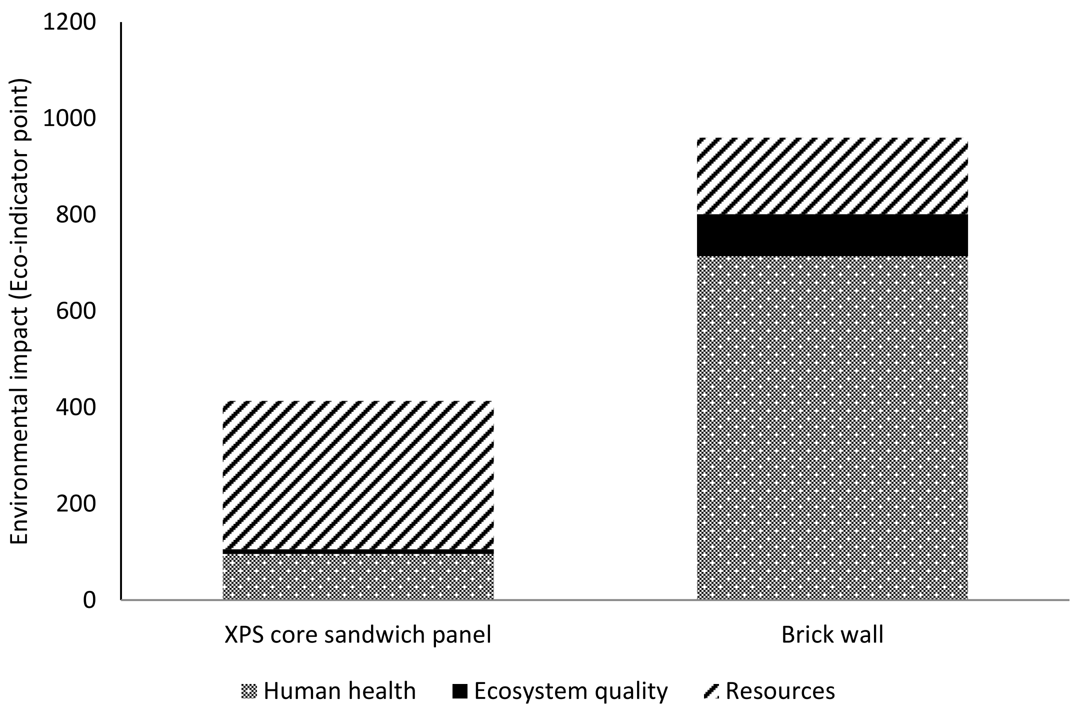

Fig. 3.2. Environmental impacts of composite and masonry buildings

3.4 Conclusions

This article discusses the use of sandwich-structured composite as novel building material. The proposed structure was compared with brick masonry structure in order to highlight the benefits and drawbacks of composites as construction materials in terms of environmental impact. Results obtained for a single family, single storey house point out that the use of the sandwich-structured composite has 43 % less environmental impact performed by *Eco-indicator 99 H/A* impact assessment method. One of the main reasons of this reduction can be due to low weight of materials in sandwich-structured composite building. This characterization would be a key advantage in future use of this material in modular and prefabrication constructions.

As the functional unit of comparison was a whole building, both scenarios were designed considering technical requirements of building such as mechanical, thermal, acoustics and fire performance properties. Therefore, some dimensions such as thickness of walls are different in two scenarios to meet those requirements. In case of comparison of specific components of the building such as roof, floor, etc., different dimensions may be considered.

Finally, it must be highlighted that the main environmental impact of the proposed structure lies in the "resources" category, which emphasizes the composite's environmental advantages in terms of "ecosystem quality" and "human health" in comparison with typical masonry building.

Acknowledgement

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CHAPTER 4 THERMAL ANALYSIS

- This chapter is published as "Samani, P., Leal, V., Mendes, A., & Correia, N. (2016). Comparison of passive cooling techniques in improving thermal comfort of occupants of a pre-fabricated building. Energy and Buildings, 120, 30-44."

Abstract

Pre-fabricated composite buildings are proposed as sustainable sheltering and housing solutions for developing countries. This work compares different passive cooling techniques of shading, natural ventilation, cool painting and increase in thickness of interior gypsum plaster for these buildings to tackle overheating in hot climates. The studied techniques are measured and compared in terms of indoor air temperature by calculating four indicators of maximum, minimum, average of highest 5 % and average of lowest 5 % temperatures as well as thermal comfort of the occupants based on two acceptability rates of ASHRAE 55 and three acceptability limits of EN 15251 standards in three climates: Porto, Nairobi and Mumbai. The findings of this comparison bring insights into the effectiveness of passive cooling techniques, that can be highly beneficial at design level. Results point out improvements by all studied techniques, even if these quantitatively depend on the presence of the occupants and the choice of the performance indicators. Finally, further indicators such as stored heat, solar radiation heat gain and surface temperature are analyzed, to explain causes and effects associated with studied passive cooling techniques. Results of these comparisons pointed out that the combined implementation of all techniques combined is effective enough to provide thermal comfort of the occupants during almost all annual occupancy in Nairobi measured by acceptability rate of 80 % of ASHRAE 55 and Category III of EN 15251.

Keywords: Cool painting; Gypsum plaster; Natural ventilation; Passive cooling, Pre-fabricated building; Shading; Adaptive thermal comfort

Nomenclature

A	Surface area [m^2]
A_o	Opening area of window [m^2]
C_d	Discharge coefficient for opening
C_w	Opening effectiveness
d_{EMPD}	Effective moisture penetration depth [m]
ε	Thermal absorptance
F_s	Open area fraction
g	Standard gravity [$m \cdot s^{-2}$]
h_m	Airside convective mass transfer coefficient [$kg \cdot m^{-2} \cdot s^{-1}$]
Q	Ventilation flow rate due to wind and stack effects [$m^3 \cdot s^{-1}$]
Q_s	Volumetric air flow rate due to stack effect [$m^3 \cdot s^{-1}$]
Q_w	Volumetric air flow rate driven by wind [$m^3 \cdot s^{-1}$]
T	Temperature [ºC]
t	Time-step
T_c	Comfort temperature [ºC]
T_{mo}	Monthly mean outdoor air dry-bulb temperature [ºC]
T_o	Outdoor air dry-bulb temperature [ºC]
T_{ot}	Operative temperature [ºC]
T_{rm}	Weighted mean of the previous 7-day outdoor air dry-bulb temperature [ºC]
T_z	Zone air dry-bulb temperature [ºC]
u	Moisture capacitance [$kg \cdot kg^{-1}$]
U-value	Overall heat transfer coefficient [$W \cdot m^{-2} \cdot K^{-1}$]
V	Outdoor wind speed [$m \cdot s^{-1}$]
α	Solar absorptance
ΔH_{NPL}	Height from midpoint of lower opening to the neutral pressure level [m]
ρ_m	Dry bulk density of material [$kg \cdot m^{-3}$]
ω	Humidity ratio [$kg \cdot kg^{-1}$]

ω_z	Zone humidity ratio [$kg \cdot kg^{-1}$]

Abbreviations

ASHRAE	American society of heating, refrigerating and air conditioning engineers
CTF	Conduction transfer function
EMPD	Effective moisture penetration depth
GHI	Global horizontal irradiance [$kWh \cdot m^{-2} \cdot day^{-1}$]
GWP	Global warming potential
HVAC	Heating, ventilating, and air conditioning
IWEC	International weather for energy calculations
NPL	Neutral pressure level
PPD	Predicted percentage of dissatisfied
UHI	Urban heat island
WMO	World meteorological organization

4.1. Introduction

At the start of the millennium, more than one billion people lived in inadequate housing, particularly in poor countries [1]. By 2030, this number may increase to 3 billion, i.e. 40 % of the global population, mainly in Sub-Saharan Africa and south Asia [2]. Moreover, noting the climate change and consequent drastic increase in natural disasters [3,4], there is a growing interest in development of sheltering and temporary housing for post-disaster situations. Considering the importance of economic viability of sheltering and housing solutions, the concept of affordable housing has been developed and investigated in recent years. Furthermore, environmental concerns of using natural resources for construction and operation of buildings have been widely vented. Linking affordable and environmental friendliness with well-being of the occupants, as social aspect of sustainability, have led to development of the concept of "sustainable building" as a basic requirement for the construction industry.

Advantages such as rapid construction, minimal handling, improved surface quality, lower need for resources and less waste have led to growth of pre-fabricated (off-site) construction [5,6]. There is also a rising interest in use of composite wall systems in pre-fabricated buildings due to benefits such as light weight and better health and safety for workers [6]. Hence, pre-fabricated composite buildings are being proposed as sustainable solutions for where there is a huge need for affordable housing (such as Sub-Saharan African countries) [2] and as a rapid post-disaster sheltering where there is high vulnerability to natural disasters (such as south Asian countries) [7]. However, considering high outdoor air temperature in both of these regions, avoiding overheating in buildings is a big challenge that needs to be tackled.

Passive cooling is a set of sustainable techniques for cooling buildings by natural means [8]. It comprises any system that aims to minimize, or eliminate if possible, mechanical air conditioning and therefore reduces cooling energy demand [9,10]. Noting that refrigeration and air conditioning account for about 15 % of global electricity consumption and may cause contamination problems due to presence of organic dust in cooling coils, fans and filters [11], passive cooling plays an important role in the sustainable development of the building industry. A widely accepted framework to engineer passive cooling systems consists of three steps: 1) prevention of heat gains; 2) modulation of heat gains and 3) heat dissipation [11]. Consequently, passive cooling techniques range from choosing the most favorable arrangements of fenestration to implementing thermal insulation, thermal mass or phase change materials. Ultimate goal of all these techniques is to reduce high indoor air temperatures and cooling energy consumption and provide acceptable thermal comfort and indoor air quality for the occupants [11-13].

Windows are the most significant components of buildings in terms of comfort and energy use per unit surface area [14]. Using shading devices is one of the most common strategies to decrease heat gains through fenestrations. Moreover, when the outdoor temperature is below the indoor temperature, e.g. during nighttime, natural ventilation through windows can be applied to dissipate the daily heat gain. Furthermore, radiation properties of the exterior surfaces of building envelope affect surface temperature and consequently heat flux [15]. Applying cool (high reflectance and emittance) paints in the façade and roof of buildings is another technique for reducing the indoor air temperature [16-18] since it reflects the incident solar radiation away and radiates the heat at night [19]. Due to several characteristics such as sound insulation, fireproofing, thermal and moisture buffering and cost, gypsum plaster has been used for thousands of years in many buildings for both interior and exterior walls and ceilings [20-22].

In this article we compare the impact of different passive cooling techniques for a pre-fabricated building made of a sandwiched-structured composite. Toward this aim, the thermal performance of the building (located in Porto, Portugal) was firstly assessed with regards to annual variations of indoor air temperature of living room and sleeping room. Subsequently, the average daily indoor air temperature was calculated for three coldest and hottest days of year. These results demonstrated the relative and absolute effectiveness of four passive cooling techniques (shading, natural ventilation, cool painting and increased thickness of interior gypsum plaster) for indoor air temperature by calculating four indicators of maximum, minimum, average of highest 5 % and average of lowest 5 % temperatures. Afterwards, the impact of the best solution of each passive cooling technique was compared in different climates in terms of average indoor air temperature as well as thermal comfort of the occupants based on two acceptability limits of ASHRAE 55 and three acceptability limits of EN 15251 standards. Three cities of Porto (as representative of warm-summer Mediterranean climate), Mumbai (where there is a high potential need for post-disaster sheltering and as representative of tropical climate) and Nairobi (where 60 % of the population lives in informal dwellings [2] and as representative of Sub-Saharan Africa) were selected for these comparisons. The study also looks at the impact of the selected passive cooling techniques on the annual heat storage energies, maximum and average annual solar radiation heat gain per area and maximum surface temperature of exterior walls and roof.

4.2. Literature review

Several studies have addressed thermal comfort to demonstrate the impact of passive cooling in buildings. ASHRAE 55 [23] standard describes thermal comfort as a state of mind which expresses satisfaction with the thermal environment [24]. Firstly, Fanger [25] defined a predicted mean vote (PMV) index as a thermal comfort vote based on four parameters: air temperature, mean radiant temperature, air velocity and air humidity and two individual parameters of clothing insulation and activity level. The PMV index is a value on a 7-point scale that assigns -3 for cold, -2 for cool, -1 for slightly cool, 0 for neutral, +1 for slightly warm, +2 for warm and +3 for hot thermal sensations. Predicted percentage of dissatisfied (PPD) is a function of PMV index that identifies the percentage of the occupants that are dissatisfied with the thermal conditions [26,27]. Noting that the Fanger model was based on large sample of college age students, impact of factors such as age, gender and body fat on accuracy of the model is questionable [28]. De Dear and Brager [29] subsequently introduced adaptive model that, as its name explains, assumes people adapt to thermal conditions by modifying their clothing insulation, posture and activity.

In hot climates, a significant fraction of heat gain happens through exterior windows [30,31]. Windows normally have a *U-value* five to ten times higher than wall area [32] therefore providing that shading devices are particularly important in terms of energy saving and thermal and visual comfort [33,34]. There is a large volume of published studies describing the role of shading devices in improving thermal comfort of the occupants of buildings. These studies examined several factors such as area and angle of the shading device [33,35,36], shading effect of surrounding objects such as trees or buildings [12,17,37,38], the window to wall ratio [30,39], color of shading [40,41], use of overhang [30,31,33,34,42] and interaction with occupants [32,43-45]. Together, these studies provide important insights into optimum design of shading device as well as energy saving benefits of shading. Nonetheless, considering low thermal inertia of the studied prefabricated building and limited space for the occupants, investigating the impact of different types of shading draws our attention to their effectiveness in comparison with other selected passive cooling techniques.

Natural ventilation, also known as free cooling, has been used for centuries. However, there is a growing interest in the use of natural ventilation not only to reduce cooling energy consumption, but also to increase indoor air quality by reducing mechanical ventilation [46-51]. This technique is especially effective for hot-dry climates and can do much to achieve the ideal indoor air temperature [49]. Overall, these studies have mainly pointed out the importance of natural ventilation in managing high indoor air temperatures. In addition to experimental, analytical and theoretical models, more contemporary trends such as computational techniques and software simulations have been used to study impact of natural ventilation on thermal performance of buildings [47]. However, modeling of natural ventilation and reliability of simulation results have been questioned by countless scholars [13,50,52,53].

Several studies have highlighted benefits of using cool painting for façades and roof of buildings. Many studies [15-17,19,54] have discussed how cool painting can contribute in diminishing urban heat island (UHI) effect in densely inhabited environments. Susca [55] has drawn our attention to impact of cool roof on global warming potential (GWP). On the other hand, results of studies by Rossi *et al.* [56] and Sproul *et al.* [57] prove that cool roof is a suitable approach to tackle global warming. Longer life than hot roofs of same material [17] and null cost for implementation [17,56] are other discussed advantages of this technique while increasing heating energy is concluded as its drawback [18]. Therefore, for climates with long winter period, it is suggested that application of cool paint should be associated with higher insulation level of the building envelope [16,58]. In addition to energy demand, other indicators such as thermal comfort [59,60], heat flow [60], heat flux [15,61,62] and surface temperature [15,61-63] have been measured to highlight the impact of cool painting. Taken together, these studies indicate that exclusive evaluation of energy consumption would not be sufficient for the impact assessment of cool painting as it is highly dependent to type of building and insulation.

Perhaps because gypsum plaster is a traditional material which is commonly used to allow wall finishing has meant that far less attention has been paid to it in buildings, even though it possesses significant thermal, acoustic and fire resistance properties [22,64,65]. Former studies show that that gypsum plaster can play a vital role in the moisture buffering [66,67] and improving thermal insulation [21,68] of buildings, there are relatively few studies discussing how use of gypsum plaster can improve thermal comfort of the occupants though. Knowing advantages of moisture buffering of gypsum plaster, this lack of interest can be due to neglecting moisture transfer in the used heat balance algorithms in some models. Woods *et al.* [69] and Qin *et al.* [70] have argued while moisture sorption of materials is one of the main factors affecting indoor humidity, it is often neglected in energy models of buildings. Moreover, Firląg and Zamada [71] and Zhang *et al.* [72] have pointed out that this element has the largest and most immediate influence on indoor air humidity. Liu *et al.* [73] have mentioned that the effect of moisture buffering is even more significant in hot-humid climates. Overall, these studies outlined the need to consider moisture transfer and storage in building models. Moreover, they indicate the importance of interior layers of building envelope on energy demand and thermal comfort of the occupants. This consideration may highlight the benefits of using interior gypsum plaster in buildings for improving indoor thermal comfort of occupants.

The former studies on applying passive cooling technique to improve indoor thermal comfort can be categorized into two groups: The first group comprises those attempts that were applied on existing buildings (retrofitting) with the ultimate goal of improving thermal comfort of the occupants and decreasing energy demand such as [26,31,36,37,48,74-76]. The second class consists of those studies that compared different techniques for a specific building, but in different climate conditions and mainly different cities of a country such as Australia [24], Brazil [62,77], France [78], Greece [79], Italy [16,30], Portugal [18] and the United States [51]. While results of the first group can be beneficial for the buildings with same characteristics in similar climates, generalization of outcomes for other climates is yet questionable. Therefore, using different climate types for each case study, especially those buildings that are at design stage, is suggested.

Regarding the influence of simulation tools on accuracy of models is another issue in these studies to be noted. Various studies have used available simulation tools such as *EnergyPlus* [16,36,39,52,79,80], *TRNSYS* [13,50,58,71,73,78,81], *ESP-r* [18,35,37,38] and *IES* [42,75,82] to simulate thermal performance of buildings. Johnson *et al.* [83] have compared different simulation tools for air flow network of natural ventilation and concluded that there would be up to 30 % error in their modeling. Noting that accuracy and capabilities of different simulation tools can vary depending on the object of study, selection of correct simulation tool for that specific purpose is essential. Moreover, the importance of different heat and mass transfer algorithm, numerical models and presumed coefficients that are often neglected.

4.3. Methodology

4.3.1 Reference building

In this research, a 6 m^2 × 5 m^2 one-story house, lined up with north, consisting of one living room, one sleeping room and a service room was considered as shown in Fig. 4.1. All walls, floors and roofs of the studied buildings are made of a sandwich-structured composite comprising two glass-fiber reinforced laminates sandwiching a light core. The core material is extruded polystyrene and Equibiaxial (EBX) woven roving of fiberglass with ±45º orientation was considered as reinforcement and epoxy as resin. Mechanical, thermal, acoustic and fire performance tests were performed to assure the proposed panel has required properties to be used as building material. Results of these tests and material selection process are presented in Samani *et al.* [84]. Exterior walls, roofs and floors are coated with a 10 mm layer of interior gypsum plaster making total thickness of 92 mm and *U-value* of 0.445 $W \cdot m^{-2} \cdot K^{-1}$. Interior walls are covered with gypsum plaster on both side (each 10 mm) resulting in total thickness of 102 mm and *U-value* of 0.44 $W \cdot m^{-2} \cdot K^{-1}$. Windows are made of double clear glazing with thickness of 32 mm and *U-value* of 2.67 $W \cdot m^{-2} \cdot K^{-1}$ and doors are wooden with thickness of 30 mm and *U-value* of 5 $W \cdot m^{-2} \cdot K^{-1}$.

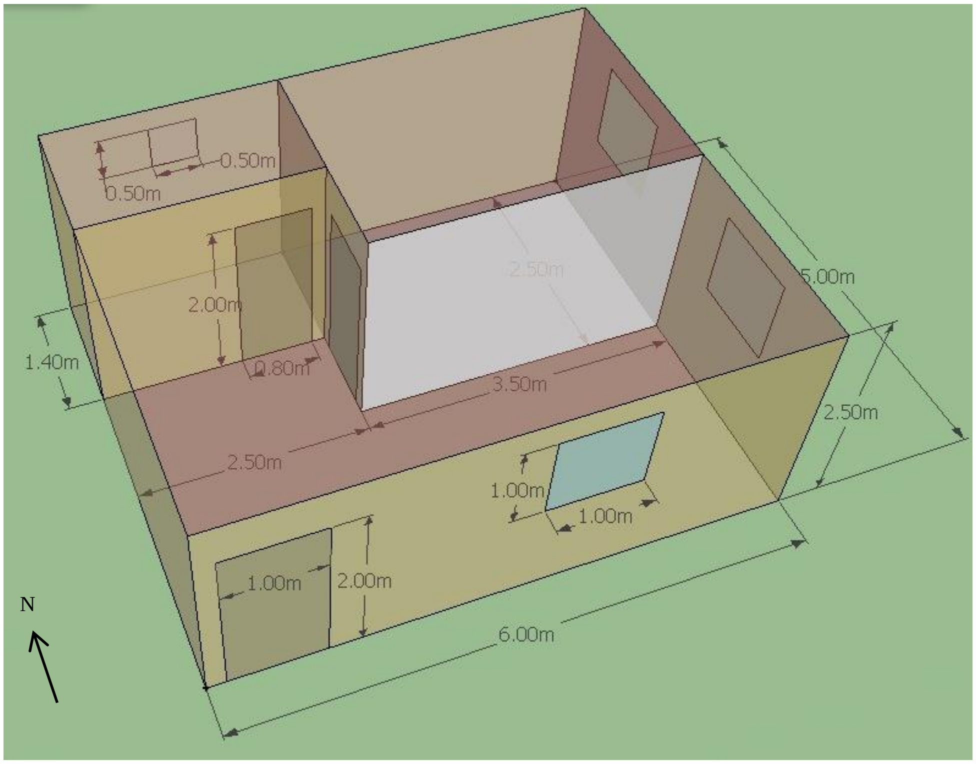

Fig. 4.1. Schematic model of the studied building

Different parameters must be set in order for thermal behavior of the building to be modelled appropriately. Infiltration, i.e. flow of outdoor air into a building through exterior doors, cracks and other unintentional openings [85], was set to 0.6 air changes per hour and air velocity of indoor space was set to $0.2\ m \cdot s^{-1}$. Internal gains from lighting, home appliances and occupants are notable elements in indoor thermal balance of the building. These gains contain sensible (convective plus radiative) and latent heat. For each zone, internal gains consisting of home appliances, lighting and occupants were defined with a daily schedule recurring all days of year as set out in Table 4.1. Power of home appliances and lights were selected based on available commercial products and fraction radiant and metabolic rate of different activities of occupants were defined based on American society of heating, refrigerating and air conditioning engineers (ASHRAE) handbook of fundamentals [85].

Table 4.1. Internal gains of the studied building

Thermal zone	Area [m^2]	Daily schedule	Type of internal gain	Activity level per person / power [W]
Living room	17.75	7:30–8:30 and 18:30-22:30 during weekdays, 7:30-22:30 during weekend	4 People seating	108
Living room	17.75	7:30–8:30 and 18:30-22:30	Lighting	36
Living room	17.75	7:30–8:30 and 18:30-22:30 during weekdays, 7:30-22:30 during weekend	Home appliances	160
Living room	17.75	24 hours	Refrigerator	28
Sleeping room	8.75	22:30-23:00	4 People reclining	81
Sleeping room	8.75	22:30-23:00	Lighting	36
Sleeping room	8.75	23:00-7:30	4 People sleeping	72
Service room	3.50	7:30–8:30 and 18:30-22:30	0.1 Person (average)	126
Service room	3.50	7:30–8:30 and 18:30-22:30	Lighting (average)	3.6

4.3.2 Simulation

EnergyPlus ver 8.1 was used as the main simulation tool and *OpenStudio ver. 1.4* as an auxiliary interface. While the simulation was performed on a yearly basis, time was discretized into a series of bins and, for each of these moments, the model equations were solved by the software [86]. As some previous works such as by Corbin *et al.* [87] and by Hong *et al.* [88] have highlighted the impact of time-step on accuracy of simulation results, number of time-steps per hour was set to 60 to run the model at each minute. Specifications of materials of the building were provided either by the manufacturer or building component library and dataset of the software.

As mentioned in the literature review, considering moisture transfer in the thermal model of the building is relevant. Therefore, conduction transfer function (CTF), as a sensible heat diffusion technique, coupled with effective moisture penetration depth (EMPD), as an inside surface moisture storage, was selected as heat and moisture transfer technique for surface assemblies of the building. Furthermore, an integrated analytical solution was used to calculate zone air temperature and humidity ratios. Regarding convective heat transfer, Costanzo *et al.* [80] have compared applicable techniques for calculating exterior convective heat transfer coefficient in *EnergyPlus* and concluded that adaptive technique provides more reliable results. Therefore, in this research the adaptive technique was selected for calculating both interior and exterior convective heat transfer coefficients. This technique classifies surfaces into four different categories based on wind and heat flow directions and defines two types of forced and natural convective heat transfer coefficients for each group. Furthermore, a predictive dynamic clothing insulation technique as a function of outdoor air temperature, as approved by the ASHRAE, was considered for clothing of the occupants.

The simulations were performed in free-floating mode which considers no HVAC (heating, ventilating, and air conditioning) system. Two main thermal zones of the building, i.e. living room and sleeping room, were analyzed in each simulation using different indicators. Prior to applying passive cooling techniques, annual variations of indoor air temperature were calculated for the studied building in Porto climate. These variations provided a baseline relating the instants during the day and throughout a year, when indoor air temperature is excessively high or low. Moreover, the indoor air temperature was compared with outdoor air dry-bulb temperature of coldest and hottest days of the year. Obtaining from weather data, July 6th, August 10th and August 31st were identified as three hottest and January 2nd, January 3rd and December 16th as three coldest days of year in Porto. Results of each of these three days were measured and averaged to assess thermal performance of the building in the hottest and coldest days of year.

As mentioned in the literature review, different indicators have been used in former studies to assess thermal behavior of buildings. In this work, impact of passive cooling techniques was inspected though 1) average indoor air temperature of living room and sleeping room; 2) thermal comfort of the occupants; 3) heat storage, solar gain and surface temperature at the exterior walls and roof. For the indoor air temperature, maximum, minimum, average of highest 5 % and average of lowest 5 % temperatures were calculated. For the walls and roof, annual heat storage energies, annual average solar radiation heat gain per area and maximum surface temperature were inspected. Furthermore, thermal comfort of the occupants was analyzed based on two adaptive models of the most widely used standards, i.e. ASHRAE 55 [23] and EN 15251 [89]. For ASHRAE 55 standard, both 80 % and 90 % acceptability limits were observed and three acceptability limits of category I (90 %), category II (80 %) and category III (65%) were considered based on EN 15251 standard. Fig. 4.2 presents breakdown of the measured indicators in this study. For annual variation of indoor air of living room and sleeping room and relation with outdoor air temperature for three coldest and hottest days of year as well as heat storage, solar gain, and surface temperature, the building was placed in Porto. For comparison of best solution of each passive cooling technique in terms of average indoor air temperature and thermal comfort of the occupants, all three climates of Porto, Mumbai and Nairobi were investigated to highlight impact of climate type on effectiveness of passive cooling techniques. Table 4.2 provides climate characteristics of these three cities.

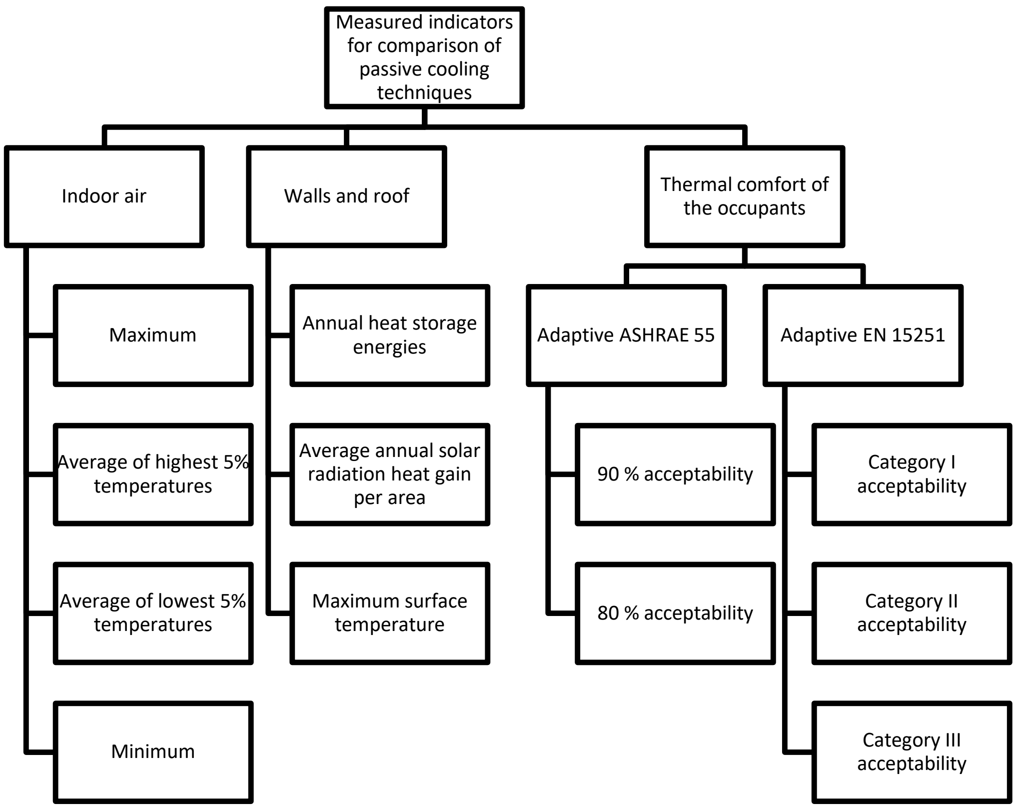

Fig. 4.2. Indicators assessed in the simulations

Table 4.2. Characteristics of adapted climates in simulations

Location	Porto, Portugal	Mumbai, India	Nairobi, Kenya
Weather file	IWEC, WMO 085450	IWEC, WMO 430030	IWEC, WMO 637400
Latitude [deg]	N 41° 13'	N 19° 7'	S 1° 19'
Longitude [deg]	W 8° 40'	E 72° 50'	E 36° 55'
Elevation [m]	73	14	1624
Cooling degree days (base 25 ºC)	36	1197	67
Heating degree days (base 18 ºC)	1433	0	305
Highest average monthly temperature [ºC]	19.4	30.0	20.8
Lowest average monthly temperature [ºC]	9.4	23.3	16.7

Annual average solar global horizontal irradiance (GHI) [$kWh\cdot m^{-2}\cdot day^{-1}$]	4.35	5.90	5.93
Köppen classification	Csb (warm-summer Mediterranean climate)	Aw (tropical savanna climate)	Cwb (subtropical highland variety of Oceanic climate)
ASHRAE climate zone	3C (warm-marine)	1B (very hot-dry)	3A (warm-humid)

4.3.3 Passive cooling techniques

4.3.3.1 Shading

Different types of shading were investigated in this study to assess their impact on indoor air temperature, i.e. average indoor air temperatures for living room and sleeping room and thermal comfort of the occupants. The same shading material was considered for all shading types with thickness of 10 mm, thermal conductivity of 0.1 $W\cdot m^{-1}\cdot K^{-1}$ and distance of 5 mm to the glazing. Three examined types of shading were inside of the window (interior shade), outside of the window (exterior shade) and between glass layers (middle shade). Activation of shading was conditioned to indoor air temperature reaching 24 ºC and applied to all fenestrations of the building.

4.3.3.2 Natural ventilation

Natural ventilation is normally simulated through opening of windows [53]. Wind and stack effects are two types of physical phenomena that induce natural ventilation in buildings. Natural ventilation because of the wind effect is explained by the pressure difference generated by the wind while the stack effect (thermal buoyancy) is based on density and temperature difference between the indoor and outdoor air [48,78]. The previous studies have mainly used wind-driven, buoyancy-driven and the combination of both effects to model natural ventilation in buildings. In this study, both wind and stack effects were considered in accordance with ASHRAE handbook of fundamentals [85] to assess their impacts on indoor air temperature and thermal comfort of the occupants. Hence, flow driven by wind Q_w and flow due to stack effect Q_s were calculated using Eqs. (4.1) and (4.2), respectively [85,86].

$$Q_w = C_w A_o F_s V \qquad \text{Eq. (4.1)}$$

$$Q_s = C_d A_o F_s \sqrt{2g\Delta H_{NPL}(|T_z - T_o| / T_z)} \qquad \text{Eq. (4.2)}$$

where A_o refers to the opening area of window and was set to 0.05 m^2 for all the windows of living room and sleeping room. F_s is the open area fraction representing the fraction of time defined for activation of opening and V is the outdoor wind speed. g refers to the standard gravity and ΔH_{NPL} represents the height from midpoint of lower opening to the neutral pressure level (NPL) which was set to 0. T_z and T_o refer to air dry-bulb temperatures of respectively thermal zone and outdoor.

Several studies such as by Heiselberg *et al.* [53], Johnson *et al.* [83] and Breesch and Janssens [50] have highlighted the importance of coefficients in modeling natural ventilation. Breesch and Janssens [50] have determined that discharge coefficient C_d and opening effectiveness C_w have the largest impact on reliability of results. While many studies have considered these two factors constant, the results obtained by Heiselberg *et al.* [53] suggest that by changing the opening area, window type and temperature difference, the discharge coefficient is different and therefore cannot be considered constant. Therefore, C_w was calculated based on the angle difference between wind direction and effective angle using Eq. (4.3) [86] that is basically a linear interpolation utilizing the values for different wind directions recommended by ASHRAE handbook of fundamentals [85]. Furthermore, C_d was calculated by Eq. (4.4) as suggested by ASHRAE handbook of fundamentals [85].

$$C_w = 0.55 - \frac{|Angle\,difference|}{180} * 0.25 \qquad \text{Eq. (4.3)}$$

$$C_d = 0.40 + 0.0045|T_z - T_o| \qquad \text{Eq. (4.4)}$$

The activation of opening was not based on fraction of time (F_s was set to 1) and three following requirements were assigned: 1) T_z > 24 ºC; 2) $T_z > T_o$ and 3) $V < 20$ m·s^{-1}. Therefore, whenever the indoor air temperature was above 24 ºC and outdoor air temperature was less than indoor air temperature, natural ventilation was activated while outdoor wind speed was less than 20 m·s^{-1}. Consequently, total ventilation flow rate Q was calculated through superposition process combining both wind and stack effects calculated using Eq. (4.5) [85,86].

$$Q = \sqrt{{Q_s}^2 + {Q_w}^2} \qquad \text{Eq. (4.5)}$$

4.3.3.3 Cool painting

ASHRAE first credited cool roofs in the Standard 90.1 [90] in 1999 characterizing them by minimum initial solar reflectance of 0.70 and minimum initial thermal emittance of 0.75 [91]. The high solar reflectance results in reduction of the amount of absorbed solar radiation in daytime and high emittance helps to dissipate the heat accumulated during day through a major radiant heat exchange at night [15-17]. In *EnergyPlus*, materials are characterized by thermal absorptance, solar absorptance and visible absorptance. Thermal absorptance ε is defined as fraction of incident long wavelength radiation that is absorbed by the material and is equal to thermal emittance for long wavelength radiant exchange. Solar absorptance α represents fraction of incident solar radiation that is absorbed by the material and is equal to 1 minus solar reflectance for opaque materials. Visible absorptance is defined as fraction of incident visible wavelength radiation that is absorbed by the material and is equal to 1 minus visible reflectance. Solar absorptance and visible absorptance are marginally different as solar radiation consists of visible spectrum along with infrared and ultraviolet wavelengths [92]. Color of exterior surfaces can be characterized by their solar absorptance [60]. Moreover, in heat transfer and radiant exchange of exterior surfaces, characteristics of most exterior layer of the surface must be considered [89]. Therefore, applying cool painting to exterior walls and roof was examined in this study by changing solar absorptance of the most exterior layer of these surfaces, i.e. exterior glass fiber laminate, and evaluating its impact on the indoor air temperature. Initial value of solar absorptance of exterior glass fiber laminate, before applying cool painting, was set to 0.3 and subsequently varied from 0.1 to 0.5 to assess the impact of color on the indoor air temperature of the building. It must be noted that *EnergyPlus* considers default values for thermal, solar and visible absorptance of building component library materials and these values need to be checked before utilization.

4.3.3.4 Thickness of interior gypsum plaster

All exterior and interior walls, roof and floor of the studied building are considered coated with interior gypsum plaster. Concerning thermal and moisture buffering advantages of gypsum plaster, impact of the gypsum plaster thickness on indoor air temperature was examined in this study. Initial thickness of gypsum plaster was set to 10 mm and subsequently varied from 2.5 mm to 20 mm. As mentioned before, EMPD coupled CTF model was selected as heat balance algorithm for surface assemblies of the building. The EMPD model considers a thin layer of uniform moisture content with thickness d_{EMPD} that dynamically exchanges moisture with the air while exposing to cycling air moisture loads. This model calculates the time derivative of moisture content by Eq. (4.6) [69]:

$$\frac{du}{dt} = \frac{\partial u}{\partial \omega}\frac{d\omega}{dt} + \frac{\partial u}{\partial T}\frac{dT}{dt} \qquad \text{Eq. (4.6)}$$

where u is the moisture capacitance of the material, ω is humidity ratio of air in equilibrium with the material, T is temperature and t is time. Moreover, uniform moisture content is a function of ω and is calculated by Eq. (4.7) [69]:

$$\rho_m A d_{EMPD} \frac{du}{dt} = h_m A\left(\omega_z - \omega\right) \qquad \text{Eq. (4.7)}$$

where ρ_m is the dry bulk density of the absorbing material, i.e. gypsum plaster in this study, A is the surface area, d_{EMPD} is effective moisture penetration depth, h_m is the airside convective mass transfer coefficient and ω_z is the humidity ratio of zone [69]. The d_{EMPD} can be determined from either experimental or detailed simulation data [86]. In this research, values for moisture properties of gypsum plaster were extracted from the software dataset.

4.3.4 Thermal comfort models

In this study, thermal comfort of the occupants was analyzed and compared for studied passive cooling techniques based on two adaptive models of the most widely used standards, i.e. ASHRAE 55 [23] and EN 15251 [89]. For ASHRAE 55 standard, both 80 % and 90 % acceptability limits were observed and three acceptability limits of category I (90 %), category II (80 %) and category III (65%) were considered based on EN 15251 standard. ASHRAE 62.2 standard [93] requires satisfaction of at least 80 % of the occupants for acceptable indoor air quality. Both ASHRAE 55 and EN 15251 standards define comfort temperature T_c based on allowed operative temperature T_{ot} (average of the indoor dry-bulb temperature and the mean radiant temperature of zone inside surfaces) related to the mean outdoor air dry-bulb temperature [86]. Therefore, ASHRAE 55 standard defines comfort temperature T_c by Eq. (4.8) where T_{mo} is the monthly mean outdoor air dry-bulb temperature [23,86].

$$\text{ASHRAE 55 } T_c: \begin{cases} T_{\text{mo}} < 10\ ^{\circ}\text{C} & \text{Not applicable} \\ 10\ ^{\circ}\text{C} < T_{\text{mo}} < 33.5\ ^{\circ}\text{C}, & T_c = 0.31 * T_{\text{mo}} + 17.8 \\ T_{\text{mo}} > 33.5\ ^{\circ}\text{C} & \text{Not applicable} \end{cases} \qquad \text{Eq. (4.8)}$$

Consequently, T_{ot} for acceptability limits of 90 % and 80 % of ASHRAE 55 standard were respectively calculated by Eqs. (4.9) and (4.10) [23,86].

$$90\ \%\ \text{acceptability limits } T_{\text{ot}} = T_c \pm 2.5 \qquad \text{Eq. (4.9)}$$

$$80\ \%\ \text{acceptability limits } T_{\text{ot}} = T_c \pm 3.5 \qquad \text{Eq. (4.10)}$$

In order to include all hours of occupants' presence in this study, for those temperatures when T_{mo} was less than 10 ºC, T_c was modified based on T_{mo} of 10 ºC that resulted in T_c of 20.9 ºC. Similarly, for those temperatures when T_{mo} was higher than 33.5 ºC, T_c was modified based on T_{mo} of 33.5 that led to T_c of 28.185 ºC. Hence, the percentage of time during annual occupancy that meets thermal comfort criteria was calculated for each passive cooling technique based on 80 % and 90 % acceptability limits of the ASHRAE 55 standard.

For the EN 15251standard, comfort temperature T_c was calculated by Eq. (4.11) where T_{rm} is weighted mean of the previous 7-day outdoor air dry-bulb temperature [86,89].

$$\text{EN 15251 } T_c: \begin{cases} T_{rm} < 10\ ^{\circ}\text{C} & \text{Not applicable} \\ 10\ ^{\circ}\text{C} < T_{rm} < 15\ ^{\circ}\text{C}, & \text{For lower limits, } T_c = 23.75\ ^{\circ}\text{C} \\ 10\ ^{\circ}\text{C} < T_{rm} < 15\ ^{\circ}\text{C}, & \text{For upper limits, } T_c = 0.33 * T_{rm} + 18.8 \\ 15\ ^{\circ}\text{C} < T_{rm} < 30\ ^{\circ}\text{C}, & T_c = 0.33 * T_{rm} + 18.8 \\ T_{rm} > 30\ ^{\circ}\text{C} & \text{Not applicable} \end{cases} \qquad \text{Eq. (4.11)}$$

Accordingly, three acceptability limits of category I (90 %), category II (80 %) and category III (65%) were respectively calculated by Eqs. (4.12), (4.13) and (4.14) [86,89].

$$\text{Category I (90 \%) acceptability limits } T_{ot} = T_c \pm 2 \qquad \text{Eq. (4.12)}$$

$$\text{Category II (80 \%) acceptability limits } T_{ot} = T_c \pm 3 \qquad \text{Eq. (4.13)}$$

$$\text{Category III (65\%) acceptability limits } T_{ot} = T_c \pm 4 \qquad \text{Eq. (4.14)}$$

In this study, to consider all hours of occupants' presence and those temperatures when T_{rm} was less than 10 ºC, T_c was modified based on T_{rm} of 10 ºC that led to T_c of 23.75 ºC. Likewise, for those temperatures when T_{rm} was higher than 30 ºC, T_c was modified based on T_{rm} of 30 ºC that resulted in T_c of 28.7 ºC. Therefore, the percentage of time during annual occupancy that meets thermal comfort criteria was calculated for each passive cooling technique based on three acceptability limits of categories I, II and III of the EN 15251 standard.

4.4. Results and discussion

4.4.1 Reference building

Figs. 4.3 and 4.4 show annual variations of indoor air temperature of respectively living room and sleeping room of the reference building, before applying any passive cooling technique. These graphs illustrate at what time of the day and when in the year the indoor air temperature reaches high and low values. Moreover, how different periods of presence of occupants and presence of home appliances affect the indoor air temperature. However, regarding the time of the year both living room and sleeping room have presented similar thermal performance.

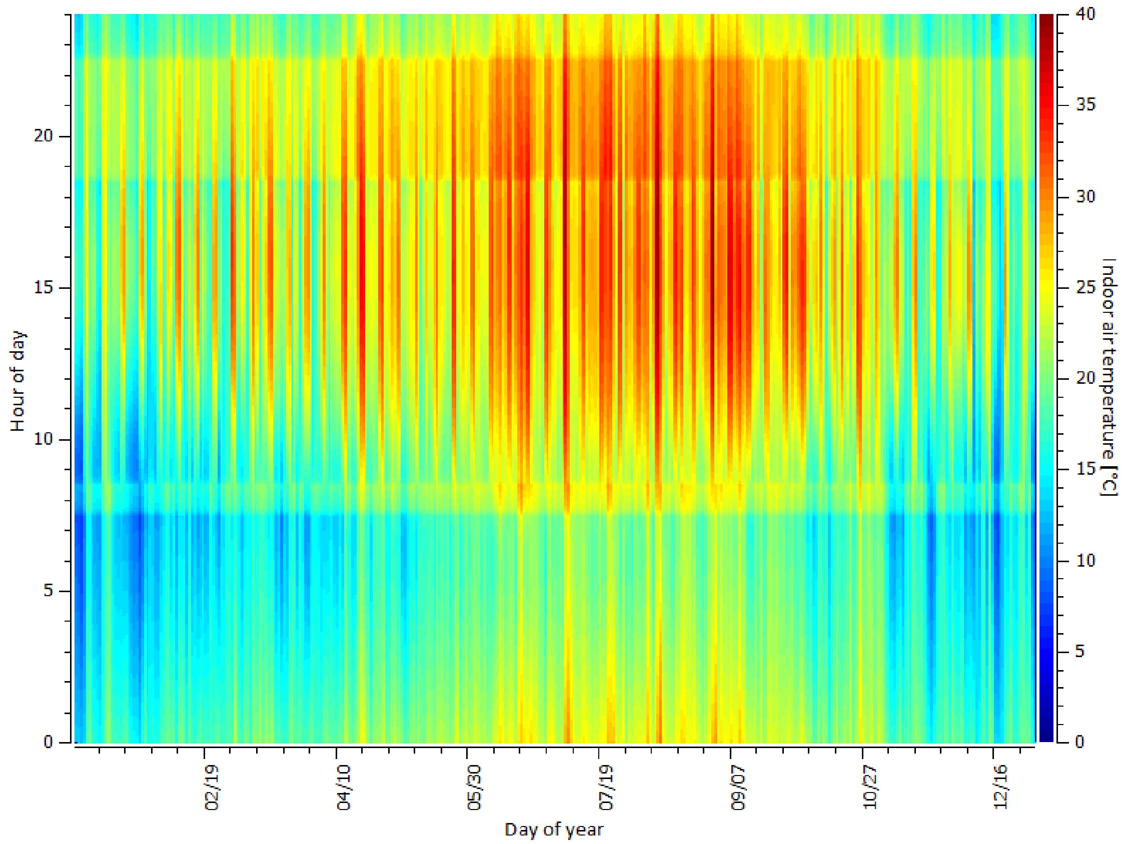

Fig. 4.3. Indoor air temperature of living room of the reference building - virtual location: Porto

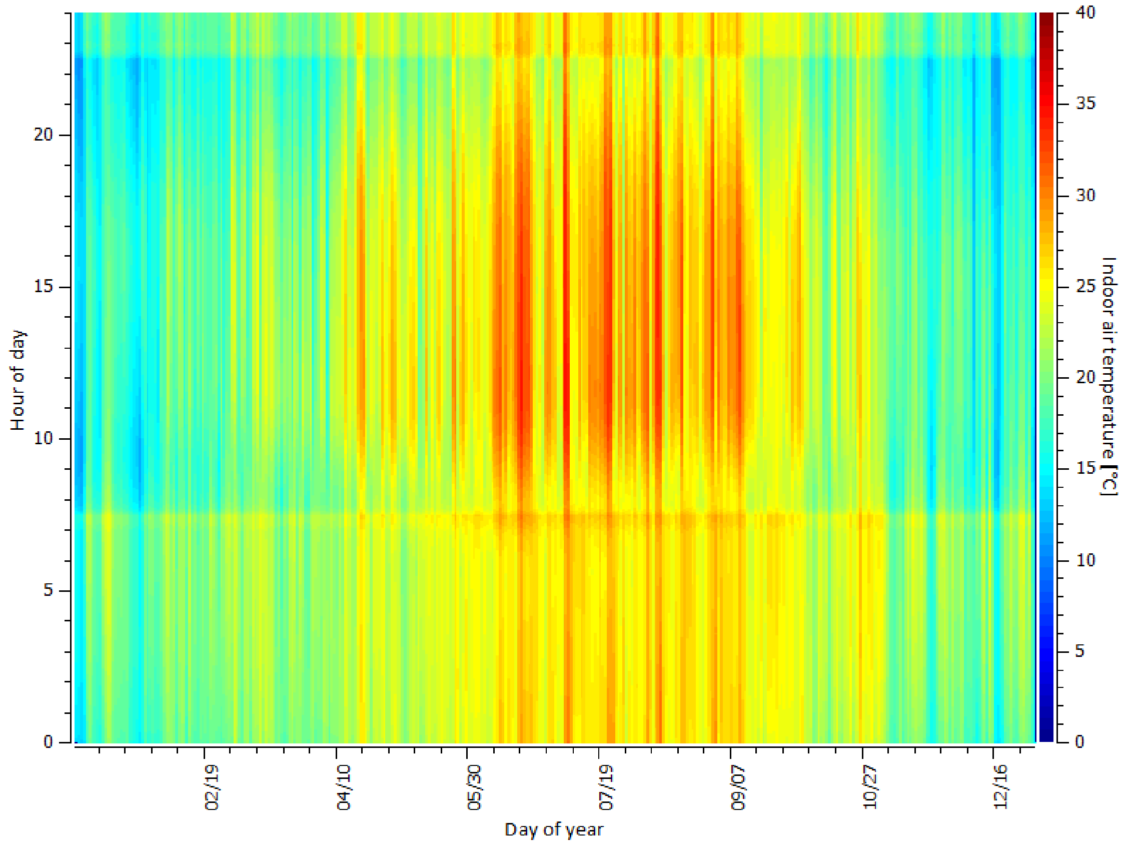

Fig. 4.4. Indoor air temperature of sleeping room of the reference building - virtual location: Porto

Figs. 4.5 and 4.6 present average indoor air temperature of living room and sleeping room as well as outdoor air temperature for respectively the three coldest and the three hottest days of year in Porto. The results show overall correspondence between outdoor and indoor air temperatures. One interesting finding of these results is high influence of presence of occupants on indoor air temperature. While in summer due to high outdoor temperature and subsequent increase in indoor air temperature this effect is less visible, the effect is more significant in winter due to lower outdoor temperature. Noting Fig. 4.6 and daily schedule of presence of occupants presented in Table 4.1, at 7.30 (marked by line A) occupants move from sleeping room to the living room. As a consequence, there is a slight boost in indoor air temperature of living room while outdoor and sleeping room air temperatures start decreasing at this instant. Similarly, when occupants shift from the living room to the sleeping room at 22.30 (marked by line B) there is an increment in indoor air temperature of the sleeping room and a reduction in indoor air temperature of the living room.

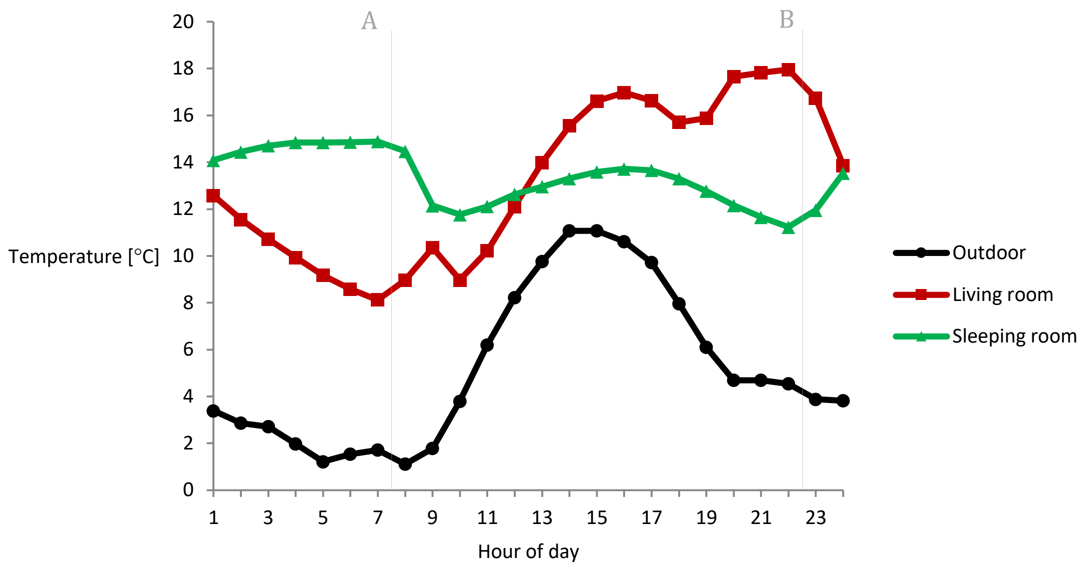

Fig. 4.5. Average daily indoor air temperature of the reference building in three coldest days of year - virtual location: Porto

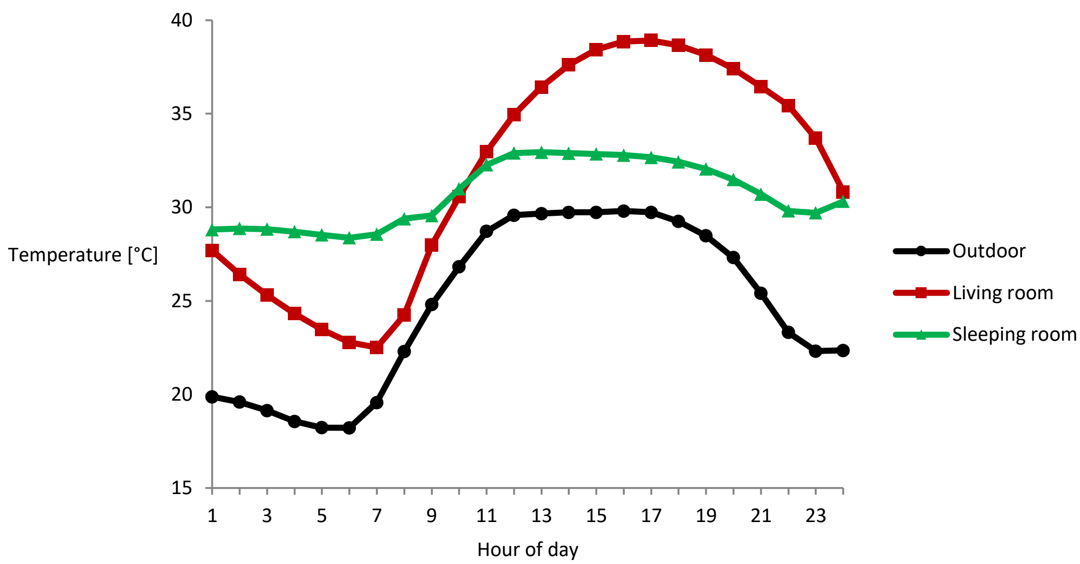

Fig. 4.6. Average daily indoor air temperature of the reference building in three hottest days of year - virtual location: Porto

4.4.2 Shading and natural ventilation

Table 4.3 compares the impact of different shading techniques and natural ventilation on average indoor air temperature of the studied building in Porto. As all of these passive cooling strategies were aimed at decreasing indoor air temperature, none has affected minimum or average of lowest 5 % temperatures significantly. Among different types of shading, exterior shade presented highest impact on reducing the indoor air temperature followed by middle shade and interior shade. Regarding impact of each technique on reduction of high temperatures, analogous decline was observed for both average of highest 5 % and maximum indoor air temperatures. However, comparing exterior shade and natural ventilation, while both have nearly equal value for average of highest 5 % temperatures, exterior shade has reduced maximum temperature 1.3 ºC more than natural ventilation.

Table 4.3. Impact of different shading techniques and natural ventilation on indoor air temperature - virtual location: Porto

	Maximum temperature [ºC]	Average of highest 5% temperatures [ºC]	Average of lowest 5% temperatures [ºC]	Minimum temperature[ºC]
Reference building	36.9	32.0	13.0	9.0
Interior shade	35.3	30.8	13.0	9.0
Middle shade	33.1	29.3	12.9	9.0
Exterior shade	32.8	29.2	12.9	8.9
Natural ventilation	34.1	29.1	13.0	8.9

4.4.3 Cool painting

Table 4.4 presents impact of solar absorptance α of exterior walls and roof on average indoor air temperature of the studied building in Porto. The results point out the reduction of both maximum and average of highest 5 % temperatures by decreasing α, i.e. painting them with a brighter color. However, a slight decrease in both minimum and the average of lowest 5 % temperature was also detected that can be considered a disadvantage of this passive cooling technique. Regarding indicators of indoor air temperature, values of maximum and average of highest 5 % temperatures presented reasonable compatibility as well as those for the minimum and average of lowest 5 % temperatures.

Table 4.4. Impact of solar absorption (α) of exterior walls and roof on indoor air temperature – virtual location: Porto

Solar absorptance (α) of exterior walls and roof	Maximum temperature [ºC]	Average of highest 5% temperatures [ºC]	Average of lowest 5% temperatures [ºC]	Minimum temperature[ºC]
0.50	37.8	32.9	13.2	9.2
0.45	37.5	32.7	13.2	9.1
0.40	37.3	32.5	13.1	9.1
0.35	37.0	32.2	13.0	9.0
0.30	36.9	32.0	13.0	9.0
0.25	36.5	31.7	12.9	8.9
0.20	36.2	31.5	12.8	8.8
0.15	35.9	31.2	12.7	8.7
0.10	35.6	31.0	12.7	8.6

4.4.4 Thickness of interior gypsum plaster

Table 4.5 illustrates the impact of the interior gypsum plaster thickness on the average indoor air temperature of the studied building in Porto. The results point out that rise in thickness of interior gypsum plaster decreases high and increases low indoor air temperatures. Concerning indicators of indoor air temperature, values of maximum and average of highest 5 % temperatures showed fitting conformity as well as those for minimum and average of lowest 5 % temperatures.

Table 4.5. Impact of thickness of interior gypsum plaster on indoor air temperature – virtual location: Porto

Thickness of interior gypsum plaster [mm]	Maximum temperature [ºC]	Average of highest 5% temperatures [ºC]	Average of lowest 5% temperatures [ºC]	Minimum temperature[ºC]
2.5	39.7	33.5	11.7	7.3
5.0	38.5	32.8	12.2	8.0
7.5	37.5	32.4	12.6	8.5
10.0	36.9	32.0	13.0	9.0
12.5	36.1	31.7	13.2	9.3
15.0	35.6	31.5	13.4	9.6
17.5	35.2	31.3	13.6	9.9
20.0	34.8	31.1	13.8	10.1

4.4.5 Comparison of techniques

After evaluating the impact of each passive cooling technique on the average indoor air temperature of the studied building, the best solution of each technique, i.e. the one resulted in topmost reduction of high indoor air temperatures, was identified to be compared in three different climates of Porto, Mumbai and Nairobi. Consequently, exterior shade was selected as the best shading technique. Moreover, cool painting of exterior walls and roof to achieve α of 0.1 and increasing thickness of the interior gypsum plaster to 20 mm were concluded as two other most advantageous techniques. Applying these three techniques in addition to natural ventilation integrated was evaluated to attain optimized model of the studied building featuring passive cooling techniques.

4.4.5.1 Comparison of techniques in terms of indoor air temperature

Tables 4.6, 4.7 and 4.8 compare the impact of each and all of passive cooling techniques on the studied building in terms of average indoor air temperature for respectively Porto, Mumbai and Nairobi climates. These results point out that all these passive cooling techniques have decreased high indoor air temperatures in all climates comparing with the reference building. Overall, exterior shading and natural ventilation showed better performance than increase in thickness of gypsum plaster and cool painting. Moreover, applying all techniques combined to the reference building proved to be highly effective to be considered as an optimized model for the building. For instance, it resulted in reduction of around 6 ºC for both average of highest 5 % and maximum temperatures in climate of Nairobi.

The results indicate that the ranking of these techniques depends on climate and use of either average of highest 5 % or maximum temperatures though. Comparing exterior shading with natural ventilation, exterior shading demonstrated better performance in Mumbai while natural ventilation proved to be more effective in climate of Nairobi. Furthermore, average of highest 5 % and maximum temperatures did not demonstrate compatibility for comparison of exterior shading and natural ventilation in climate of Porto as already discussed in the section 4.4.2. While none of these techniques were aimed at changing the low indoor air temperatures of the building in winter, considerable findings were detected regarding this matter. Increase in thickness of gypsum plaster resulted in rise of minimum and average of lowest 5 % temperatures while cool painting influenced them adversely.

Table 4.6. Comparison of impacts of different passive cooling techniques on average indoor air temperature – virtual location: Porto

	Maximum temperature [ºC]	Average of highest 5% temperatures [ºC]	Average of lowest 5% temperatures [ºC]	Minimum temperature[ºC]
Reference building	36.9	32.0	13.0	9.0
Exterior shade	32.8	29.2	12.9	8.9
Natural ventilation	34.1	29.1	13.0	8.9
Cool painting	35.6	31.0	12.7	8.6
Increase in thickness of interior gypsum plaster	34.8	31.1	13.8	10.1
All techniques combined	31.0	26.5	14.7	9.7

Table 4.7. Comparison of impacts of different passive cooling techniques on average indoor air temperature – virtual location: Mumbai

	Maximum temperature [ºC]	Average of highest 5% temperatures [ºC]	Average of lowest 5% temperatures [ºC]	Minimum temperature[ºC]
Reference building	40	37.4	25.3	21.9
Exterior shade	36.3	34.5	23.9	20.7
Natural ventilation	37.9	35.0	24.4	20.9
Cool painting	38.6	36.2	24.8	21.2
Increase in thickness of interior gypsum plaster	38.5	36.4	26.3	23.3
All techniques combined	34.5	32.2	23.7	21.3

Table 4.8. Comparison of impacts of different passive cooling techniques on average indoor air temperature – virtual location: Nairobi

	Maximum temperature [ºC]	Average of highest 5% temperatures [ºC]	Average of lowest 5% temperatures [ºC]	Minimum temperature[ºC]
Reference building	35.1	32.4	20.1	17.1
Exterior shade	32.0	29.8	19.8	17.0
Natural ventilation	31.4	28.6	19.7	16.9
Cool painting	33.9	31.5	19.6	16.8
Increase in thickness of interior gypsum plaster	33.4	31.4	20.8	18.2
All techniques combined	29.3	26.7	20.0	17.6

4.4.5.2 Comparison of techniques in terms of thermal comfort

Figs. 4.7, 4.8 and 4.9 compare passive cooling techniques in terms of selected adaptive comfort models for respectively Porto, Mumbai and Nairobi climates. This comparison points out that effectiveness of the studied techniques depends on the climate as well as the adapted thermal comfort models. Similar to the results of indoor air temperature, natural ventilation and exterior shading proved to be highly effective in improving thermal comfort of the occupants in all climates measured by all adapted thermal comfort models. Regarding cool painting, although it has decreased hours of thermal discomfort at high temperatures, noting its negative impact on low temperatures, the overall influence is less significant in comparison with natural ventilation and exterior shading. Another important finding was that even though increase in thickness of interior gypsum plaster demonstrated positive impact on indoor air temperatures in all the studied climates, thermal comfort assessment showed the contrary for the climate of Mumbai. However, it presented positive influence of this technique for the climate of Porto. This can be explained by the fact that this technique increases low indoor air temperatures that does not seems to be fully advantageous in a climate such as Mumbai where the lowest average monthly temperature is 23.3 ºC. Moreover, unlike exterior shading and natural ventilation that perform upon high indoor air temperature, the impact of higher thermal inertia provided by this technique is not necessarily concurrent with hours of occupancy. It must also be noted that the annual occupancy refers to around 70 % of the year when the occupants are in either living room or sleeping room. This period consists of all nights and does not include weekday afternoons. Therefore, this can affect the impact of studied passive cooling techniques in terms of adaptive thermal comfort compared with the indoor air temperature.

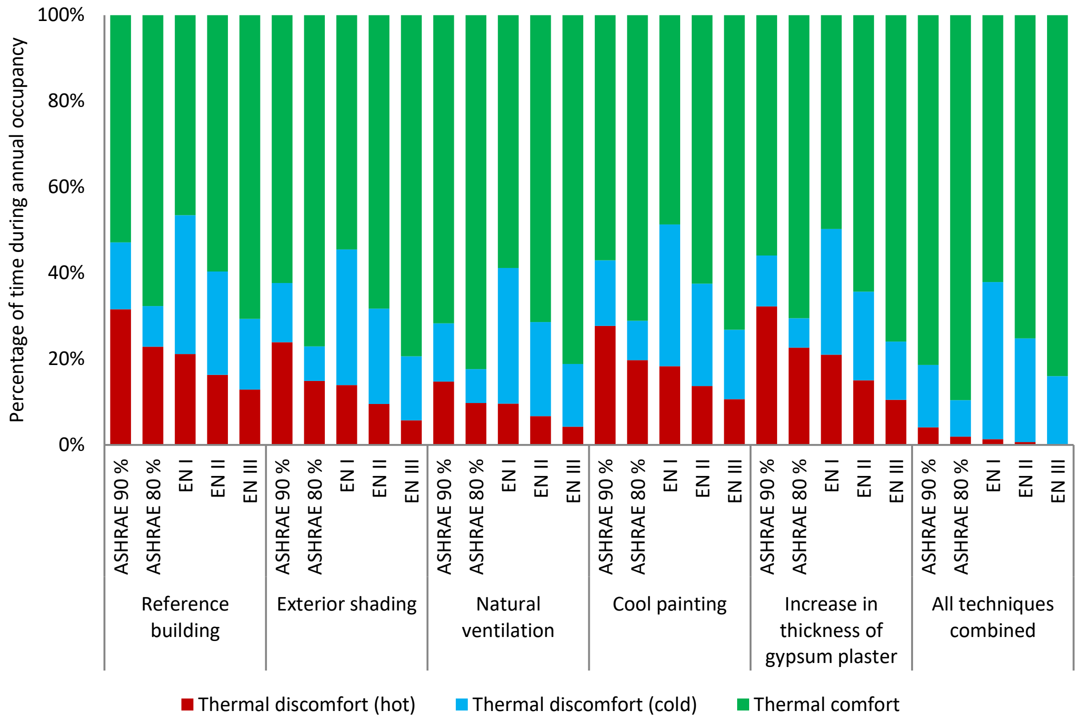

Fig. 4.7. Comparison of thermal comfort of the occupants for different passive cooling techniques – virtual location: Porto

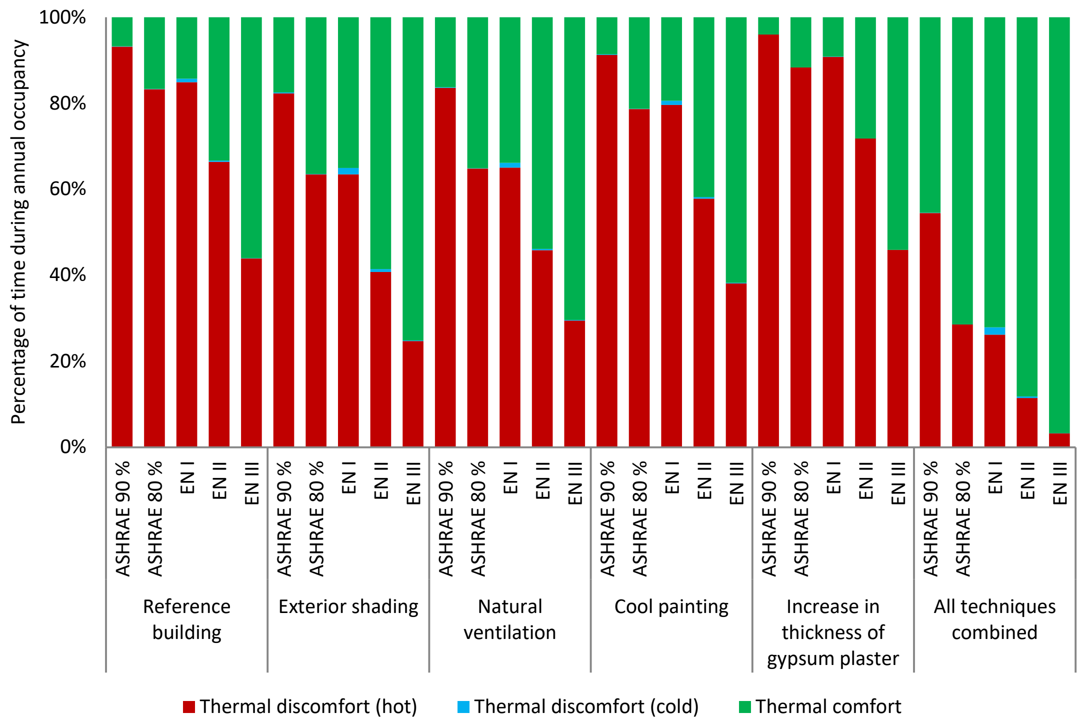

Fig. 4.8. Comparison of thermal comfort of the occupants for different passive cooling techniques – virtual location: Mumbai

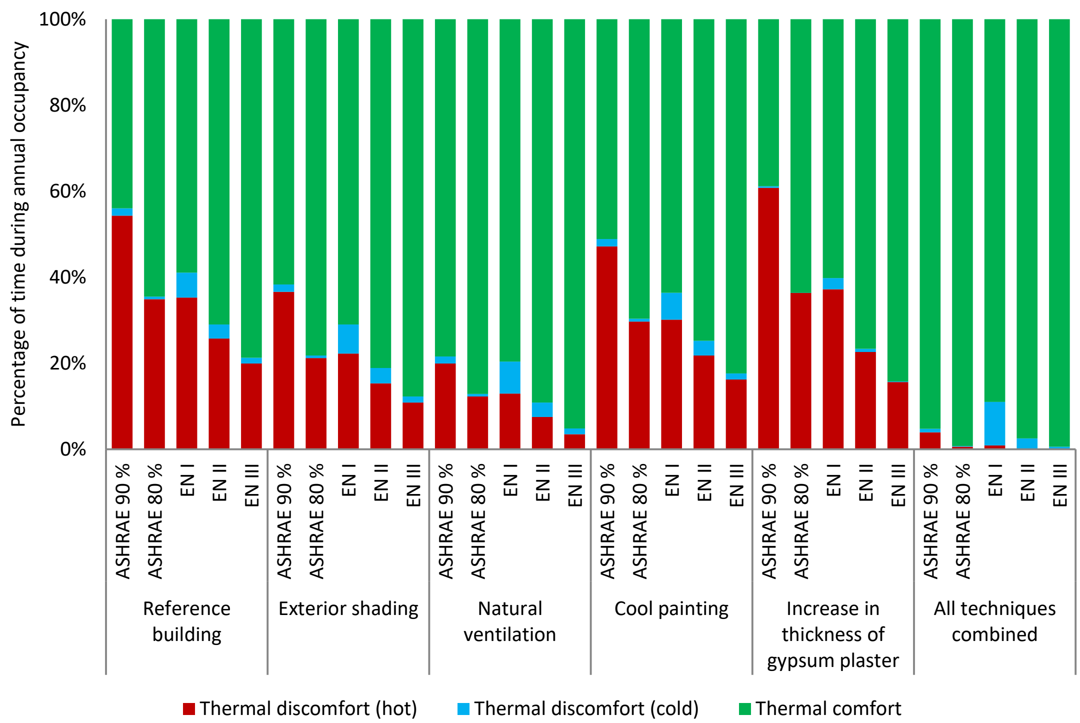

Fig. 4.9. Comparison of thermal comfort of the occupants for different passive cooling techniques – virtual location: Nairobi

4.4.5.3 Comparison of impact of techniques on exterior walls and roof

Studying other indicators in addition to indoor air temperature and thermal comfort can enlighten causes and effects associated with passive cooling techniques. Table 4.9 compares passive cooling techniques in terms of annual heat storage energies, average annual solar radiation heat gain per area and maximum surface temperature for exterior walls and roof in climate of Porto. The comparison of heat storage energies explains how increased thickness of gypsum plaster has decreased indoor air temperature by storing the heat. Moreover, the results point out how cool painting of exterior walls and roof, i.e. change of α from 0.3 to 0.1, has lowered solar radiation heat gain per area by 44 %. Furthermore, applying cool painting has resulted in reduction of 8.9 ºC in maximum surface temperature of walls and roof.

Table 4.9 Impact of passive cooling techniques on exterior walls and roof

	Reference building	Exterior shading	Natural ventilation	Cool painting	Increase in thickness of gypsum plaster	All techniques combined
Annual heat storage energies [MJ]	2.03	2.02	2.04	2.07	2.68	2.84
Average annual solar radiation heat gain per area [$W \cdot m^{-2}$]	36.78	36.78	36.78	16.22	36.78	16.22
Maximum surface temperature [ºC]	45.5	45.3	45.5	36.6	45.5	34

4.5. Conclusions

This article compared different passive cooling techniques for a pre-fabricated building made of a sandwiched-structured composite. The thermal performance of the building was firstly assessed by simulating average indoor air temperature annually and daily for the three coldest and the hottest days of year. Calculating four indicators of maximum, minimum, average of highest 5 % and average of lowest 5 % temperatures, four different passive cooling techniques (shading, natural ventilation, cool painting and thickness of interior gypsum plaster) were investigated in terms of their impact on average indoor air temperature. Afterwards, the impact of the best solution of each passive cooling technique was compared in three different climates of Porto, Mumbai and Nairobi in terms of average indoor air temperature as well as thermal comfort of the occupants based on two acceptability limits of ASHRAE 55 and three acceptability limits of EN 15251 standards. Furthermore, annual heat storage energies, average annual solar radiation heat gain per area and maximum surface temperature were inspected to assess causes and effects associated with the studied techniques. By combining the best solution of each technique, the results show that thermal comfort of the occupants is achieved during almost all annual occupancy in Nairobi climate.

Thermal analysis of the building showed a substantial impact of the presence of occupants on indoor air temperature, especially in winter. A possible explanation for this observation is the low thermal inertia of the building and limited space for the occupants. Moreover, studying indoor air temperature confirmed the positive influence of all studied passive cooling techniques on decreasing high temperatures. However, our study demonstrated the superiority of natural ventilation and exterior shading followed by cool painting and increase in thickness of gypsum plaster. Regarding performance at low temperatures, exterior shading and natural ventilation were shown to have little or no impact. Cool painting slightly decreased low temperatures, which can be explained by lower solar absorptance of exterior walls and roof. Furthermore, an increase in gypsum plaster thickness raised the lower temperature, which can be justified by the increase in thermal mass and heat storage of the building in this situation. An interesting finding on the impact of the thickness of gypsum plaster was its positive effect on both high and low temperatures, due to an increase of the thermal storage effect.

The results also highlighted significant impact of climate on effectiveness of the studied passive cooling techniques. For instance, exterior shading demonstrated larger influence in Mumbai while natural ventilation proved to be more effective in climate of Nairobi. Moreover, while increase in thickness of plaster proved to be beneficial in improving thermal comfort of the occupants in Porto by decreasing high and increasing low indoor air temperatures, it did not seem to be fully advantageous in climate of Mumbai, where the lowest monthly average temperature is 23.3 ºC. It must be noted that while exterior shading and natural ventilation are normally actuated upon high indoor air temperature, cool painting and increase in thickness of gypsum plaster are not contingent upon indoor air or comfort of the occupants.

Considering high indoor air temperatures, two indicators of maximum indoor air temperature and average of highest 5 % indoor air temperatures indicated different preeminence for some of the studied techniques. Therefore, inspecting sets of top temperatures instead of peak temperature is suggested for future studies. Considering thermal comfort of the occupants, adaptive thermal comfort models depend on presence of occupants and the hours of occupancy is around 70 % of the year including all nights and excluding weekday afternoons. Hence, it may slightly affect the impact of studied passive cooling techniques in terms of adaptive thermal comfort compared with the indoor air temperature. Moreover, ASHRAE 55 considers mean outdoor air temperature based on the last month whereas EN 15251 only considers the previous 7 days. Therefore, minor differences between hours of thermal comfort based on these two standards were expected.

Inspecting further indicators helped better explanation of the causes and effects associated with passive cooling techniques. The comparison in terms of heat storage energies showed how an increase in thickness of gypsum plaster contributes to both decreasing high and increasing low temperatures. Considering the low thermal inertia of the building, gypsum plaster increased heat storage of walls and roof and consequently balanced energy in day time and night time. Furthermore, observing solar radiation heat gain illustrated how cool painting can decrease high temperatures in hot scenarios by means of preventing heat gain. Inspecting surface temperatures also pointed out that cool painting can reduce maximum surface temperature by up to 8.9 ºC in climate of Porto. Lowering surface temperature can be important for manufacturing requirement of panels and may provide new opportunities for using alternative materials. Observing the results of this study and reviewing three types of passive cooling techniques mentioned in introduction, it can be summed up that shading and cool painting contribute in reduction of high indoor air temperatures through prevention of heat gains, increase in thickness of gypsum plaster via modulation of heat gains and natural ventilation by heat dissipation.

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CHAPTER 5 ENERGY ANALYSIS

- This chapter is submitted as "Samani, P., Mendes, A., Leal. V., & Correia, N. Pre-fabricated, environmentally friendly and energy self-sufficient single-family house in Kenya" to the Journal of Cleaner Production with manuscript number JCLEPRO-D-16-01162R1.

Abstract

Due to costly and difficult access to the power grid, only 8 % of the people have access to electricity in rural areas of Kenya. Stand-alone photovoltaic (SAPV) systems are pollution-free solutions for electrification of this region. This work provides a comprehensive approach for electrification of rural areas of Kenya through taking into account both energy demand and supply sides. Toward this, a pre-fabricated building made of a green sandwich-structured composite is assessed in rural areas of Nairobi. Two different levels of energy needs are firstly defined and annual cooling and heating energy demands to keep the occupants within the comfort temperature are calculated. Consequently, four passive cooling techniques (shading, natural ventilation, cool painting and increased thickness of interior gypsum plaster) are applied to decrease the cooling energy demand. Afterwards, A SAPV system is designed through sizing of the main components as well as determining the optimum tilt angle and azimuth for the PV array. Moreover, the impact of *LLP* on required power of PV array was investigated for each passive cooling technique. Finally, four PV technologies (monocrystalline silicon (mono-Si), polycrystalline silicon (poly-Si), cadmium telluride (CdTe) and copper indium selenide (CIS)) were assessed for the designed SPAV system and compared in terms of environmental impact and cost and CIS demonstrated the best performance in all criteria. The results highlight a reduction of about 84 % in cooling energy demand through combining all passive cooling techniques originating a house displaying passive behavior. Moreover, the SAPV system proves to be a feasible solution with significant lower cost and GHG emissions in comparison with alternative solutions. The results also outline the importance of the loss of load probability (*LLP*) in designing SAPV systems indicating a sudden increase in required power of array for *LLP*s less than 2%.

Keywords

GHG; Loss of load probability; Off-grid; Passive cooling; Sizing; Stand-alone PV system

Nomenclature

A_o	opening area of window / m^2
C_a	adjusted capacity of battery / Ah
C_b	capacity of one battery / Ah
C_d	discharge coefficient for opening
C_n	total cost in year n / $
C_u	unadjusted capacity of battery / Ah
C_w	opening effectiveness
d	real discount rate
E	energy demand per day / Wh
E_d	total energy demand per day / Wh
E_p	annual produced electric energy by SAPV system / kWh
F_c	correction factor for battery
F_s	open area fraction
F_{scc}	Safety factor for charge controller
F_{si}	Safety factor for inverter
g	standard gravity / $m \cdot s^{-2}$
GHG_b	GHG emissions of battery / t of CO_2
GHG_g	GHG emissions of grid extension PV system / t of CO_2
GHG_{kWh}	GHG emissions for production of 1 kWh by the grid extension system / t of $CO_2 \cdot (kWh)^{-1}$
GHG_{pv}	GHG emissions of PV modules / t of CO_2
GHG_s	GHG emissions of balance of system / t of CO_2
GHG_{SAPV}	GHG emissions of SAPV system / t of CO_2
I_{cc}	charge controller current / A
I_{DC}	system current / A
I_m	module current / A

I_{mpp}	current of module at maximum power point / A
I_{sc}	short circuit current of PV array / A
L	lifetime of PV system / years
$LCOE$	levelized cost of energy / $\$\cdot(kWh)^{-1}$
DoD	maximum depth of discharge
N_a	number of autonomy days
N_{bp}	number of batteries in parallel
N_{bs}	number of batteries in series
N_m	number of modules
N_{mp}	number of modules in parallel
N_{ms}	number of modules in series
P_i	power of inverter
P_{max}	maximum power of load / W
P_{mpp}	power of module at maximum power point / W
P_{pv}	power of PV array / W
PSH	peak sun hours / hr
Q	ventilation flow rate due to wind and stack effects / $m^3\cdot s^{-1}$
Q_s	volumetric air flow rate due to stack effect / $m^3\cdot s^{-1}$
Q_w	volumetric air flow rate driven by wind / $m^3\cdot s^{-1}$
T_o	outdoor air dry-bulb temperature / ºC
T_z	zone air dry-bulb temperature / ºC
U-$value$	thermal transmittance / $W\cdot m^{-2}\cdot K^{-1}$
V	outdoor wind speed / $m\cdot s^{-1}$

V_b	battery voltage / V
V_{DC}	system voltage / V
V_{mpp}	voltage of module at maximum power point / V
V_{oc}	open circuit voltage of PV array / V
ΔH_{NPL}	height from midpoint of lower opening to the neutral pressure level / m
η	efficiency of the system

Abbreviations

AC	alternating current
ACH	air change per hour
AGM	absorbent glass mat
ASHRAE	American Society of Heating, Refrigerating and Air conditioning Engineers
CdTe	cadmium telluride
CIS	copper indium selenide
DC	direct current
GHG	greenhouse gas
GHI	global horizontal irradiation
GWP	global warming potential
IEA	International Energy Agency
LCOE	levelized cost of energy
LLP	loss of load probability
Mono-Si	monocrystalline silicon
mpp	maximum power point
MPPT	maximum power point tracker

NASA	National Aeronautics and Space Administration
NPL	neutral pressure level
NREL	National Renewable Energy Lab
Poly-Si	polycrystalline silicon
PV	photovoltaic
SAPV	stand-alone photovoltaic
SHR	sensible heat ratio
UHI	urban heat island
VAV	variable air volume

5.1. Introduction

According to the International Energy Agency (IEA, 2015), about 1.5 billion people in the world do not have access to electricity. In sub-Saharan Africa, 69 % of population lack access to the electricity grid (Ondraczek, 2014) makes it the center of the energy crisis (Qureshi et al., 2016). In Kenya, while 74.8 % of population live in rural areas, only 8 % of them have access to electricity (World Bank, 2015; Sigarchian et al., 2015). Providing electricity in rural areas not only can enhance human health, economy and education but also prevents migration of people to larger cities (Alazraki and Haselip, 2007; Narula and Bhattacharyya, 2016). Currently, the most common alternative solution for rural electrification is diesel engines which are associated with high and rising fuel cost, maintenance and transportation costs, bulk storage need and massive environmental impacts (Sigarchian et al., 2015; Mebratu and Wamukonya, 2007; Izadyar et al., 2016). Many studies (Sigarchian et al., 2015; Wasike, 2015; Zoulias and Lymberopoulos, 2007; Lay et al., 2013) have highlighted high solar energy potential in Kenya. According to the meteorological data provided by National Aeronautics and Space Administration (NASA, 2015), Nairobi has daily average solar global horizontal irradiation 0f 5.93 $kWh \cdot m^{-2}$ ranging from 5.11 $kWh \cdot m^{-2}$ in June to 6.86 $kWh \cdot m^{-2}$ in February.

Safety, silence, adjustable capacity, reliability and acceptable lifetime of up to 30 years have made photovoltaic (PV) as one of the most popular renewable energy sources in the 21st century (Ali and Salih, 2013; Jia et al., 2016). Apart from the grid extension PV systems, there is an increasing interest in using stand-alone photovoltaic (SAPV) systems (also known as off-grid) for where access to power grid is costly or difficult (Ali and Salih, 2013; Rezk and El-Sayed, 2013; Kaldellis et al., 2009). These systems mainly include a renewable energy source (solar or wind power), often in combination with batteries for storage and/or diesel generator (Zoulias and Lymberopoulos, 2007; AlShemmary et al., 2013; Li and Yu, 2016; Chowdhury et al., 2015). Considering the mentioned potentials, Kenya is one of the leading SAPV market in the world and the biggest in Africa (Lay et al., 2013).

While both supply and demand sides of energy analysis are intrinsically linked, most studies have only focused on one of them. Investigating the requirements of energy demand can bring new insights into the characteristics of the supply system. Considering buildings as energy systems requires having passive behavior as their starting point so that they can fulfill the comfort of occupants with little need for “add-on” (Oliveira Fernandes, 2015). In former studies (Samani et al., 2014, 2015), a sandwich-structure composite was assessed as building material for pre-fabricated housing and significant lower environmental impacts in comparison with masonry building materials was pointed out. Concerning other advantages such as rapid construction, lower need of resources and less waste (Lawson and Ogden, 2008; Manolo, 2013), this solution can be considered as a suitable choice for sheltering and housing in Kenya. However, overheating of the building and consequent need for air conditioning is substantial due to the high outdoor air temperature. Noting that refrigeration and air conditioning account for about 15 % of global electricity consumption (Santamouris and Kolokotsa, 2013), reduction of this energy can be highly beneficial in designing new energy supply systems with less capacity. Passive cooling is one of the sustainable approaches to tackle this challenge that includes any technique aiming at reducing cooling energy demand usually through prevention, modulation and dissipation of heat gains (Borge-Diez et al., 2013; Alvarado et al., 2009; Santamouris and Kolokotsa, 2013).

In this article, the combination of passive cooling and SAPV system for a pre-fabricated building in rural areas of Nairobi, Kenya was investigated. Toward this aim, two scenarios of basic needs and ordinary needs were firstly defined for typical home appliances. Consequently, annual cooling and heating energy demands to keep the occupants within the comfort temperature were calculated. Subsequently, four passive cooling techniques (shading, natural ventilation, cool painting and increased thickness of interior gypsum plaster) were investigated to decrease the cooling energy demand. Afterwards, a SAPV system was designed through sizing of the main components (PV array and storage battery) as well as determining the optimum tilt angle and azimuth for the PV array. Moreover, the impact of *LLP* on required power of PV array was investigated for each passive cooling technique. Finally, four PV technologies (mono-Si, poly-Si, CdTe and CIS) were assessed for the designed SPAV system and compared in terms of environmental impacts and cost.

5.2. Literature review

Several studies have evaluated different sources of power generation for electrification in Kenya. Sigarchian et al. (2015) have compared PV with wind and biogas to generate power for a village in Kenya and identified PV as the most capable source. Lay et al. (2013) have assessed PV systems as source of lighting in comparison with various fuels and concluded that the selection highly depends on the income of households. Regarding type of PV system, Zeyringer et al. (2015) have compared stand-alone with grid extension and concluded that stand-alone systems are more cost-effective for electrification of rural areas. Deichmann et al. (2011) also have highlighted superiority of SAPV systems in rural areas while grid extension presented better performance in densely populated areas. On the other hand, Parshall et al. (2009) have concluded that the selection between two systems basically depends on the location and grid extension is the cheaper choice in most areas of Kenya. Together, these studies estimated an increase in use of PV systems in future in spite of high cost as the main barrier for this technology. Ondraczek (2014) has argued that most of academic publications have overestimated the cost of PV systems in Kenya and the actual cost is lower. He has also concluded that off-grid and mini-grid applications seem to be the only feasible solar options with the current situation. Zeyringer et al. (2015) also have highlighted the impact of economies of scale in comparing stand-alone and grid extension systems remarking that by increase in capacity of grid extension systems, the cost will significantly deduct. Overall, these studies indicate that solely cost-based comparative studies are only accountable at the time of research for a specific location and it is essential to consider other technical factors in assessment of PV systems for electrification.

Thus far, various studies have investigated different passive cooling techniques. For instance, former studies on shading devices have mainly focused on characteristics of shading such as area and angle of shading (Lomanowski and Wright, 2012; Cho et al., 2014; Yun et al., 2014) and window to wall ratio (Bellia et al., 2013; Tzempelikos and Athienitis, 2007) in evaluating impact of shading in energy saving. Most of the researches on natural ventilation also have concentrated on factors such as timing whether for different hours of day or night (Breesch and Janssens, 2010; Toe and Kubota, 2015; Liping and Hien, 2007; Faggianelli et al., 2014) or reliability of numerical and analytical models (Breesch and Janssens, 2010; Heiselberg et al., 2001; Belleri et al., 2014; Parys et al., 2012). Considering cool painting, in addition to its negative impact on heating energy demand (Dias et al., 2014), most of the studies have highlighted its advantages on diminishing urban heat island (UHI), global warming (Brito Filho et al., 2011; Costanzo et al., 2013; Akbari et al., 2001; Zinzi and Agnoli, 2012; Di Giuseppe and D'Orazio, 2015; Rossi et al., 2013; Sproul et al., 2014) and null cost for its implementation (Akbari et al., 2001; Zinzi and Agnoli, 2012; Di Giuseppe and D'Orazio, 2015; Rossi et al., 2013). Regarding gypsum plaster, aside from its thermal insulation advantages that have already been discussed (Barbero et al., 2014; Dylewski and Adamczyk, 2014), the moisture sorption has normally been neglected in numerical models (Woods et al., 2013; Qin et al., 2009) that can be more substantial in hot-humid climates (Liu et al., 2015). Overall, while all these studies indicate effective impact of passive cooling techniques on decreasing cooling energy demand, they have been mainly focused on one particular technique and far less attention has been paid to their comparison and integration.

The literature review shows that a number of studies have investigated energy policies and planning (Parshall et al., 2009; Williams et al., 2015; Habtetsion and Tsighe, 2007; Cherni and Preston, 2007) and energy demand (Zeyringer et al., 2015; Nzia, 2013; Fabini et al., 2014; Kaijuka, 2007) in Kenya. Moreover, numerous studies (Sigarchian et al., 2015; Wasike, 2015, Zoulias and Lymberopoulos, 2007; Ali and Salih, 2013; AlShemmary et al., 2013; Zeyringer et al., 2015; Celik, 2007) have focused on designing a SAPV system which are mainly based on economic analysis (Sigarchian et al., 2015; Wasike, 2015, Zoulias and Lymberopoulos, 2007; AlShemmary et al., 2013). Taking into account both sides of demand and supply, Zeyringer et al. (2015) have suggested detailed assessment of both energies that is often neglected in published studies. Exploring either demand or supply side, most of the studies have considered number of households (Ondraczek, 2014; Sigarchian et al., 2015; Zoulias and Lymberopoulos, 2007; Zeyringer et al., 2015; Parshall et al., 2009; Nzia, 2013; Fabini et al, 2014) rather than specific design for a particular housing solution (AlShemmary et al., 2013; Celik, 2007). Up to our knowledge, none of the former studies have investigated combination of passive cooling (as sustainable approaches to decrease energy demand) and SAPV systems as renewable energy supply.

5.3. Methods

In this part, the reference building and climate are firstly characterized. Afterwards, the scenarios for energy demand and internal gains are defined. Subsequently, four applied passive cooling techniques to reduce the energy demand are explained. Finally, the procedure for SAPV system design and environmental impacts and cost analyses are described.

5.3.1 Reference building

The reference building is a 30 m^2 pre-fabricated house located in rural areas of Nairobi encompassing one living room (17.75 m^2), one sleeping room (8.75 m^2) and a service room (3.50 m^2) as shown in Fig. 5.1. All exterior and interior walls, floors and roofs are made of a composite sandwich panel consisting of two glass-fiber reinforced laminates sandwiching an extruded polystyrene core. More details of this sandwich-structure composite are presented in Samani et al. (2015). Table 5.1 presents climate characteristics of Nairobi and Table 5.2 provides construction details of the reference building.

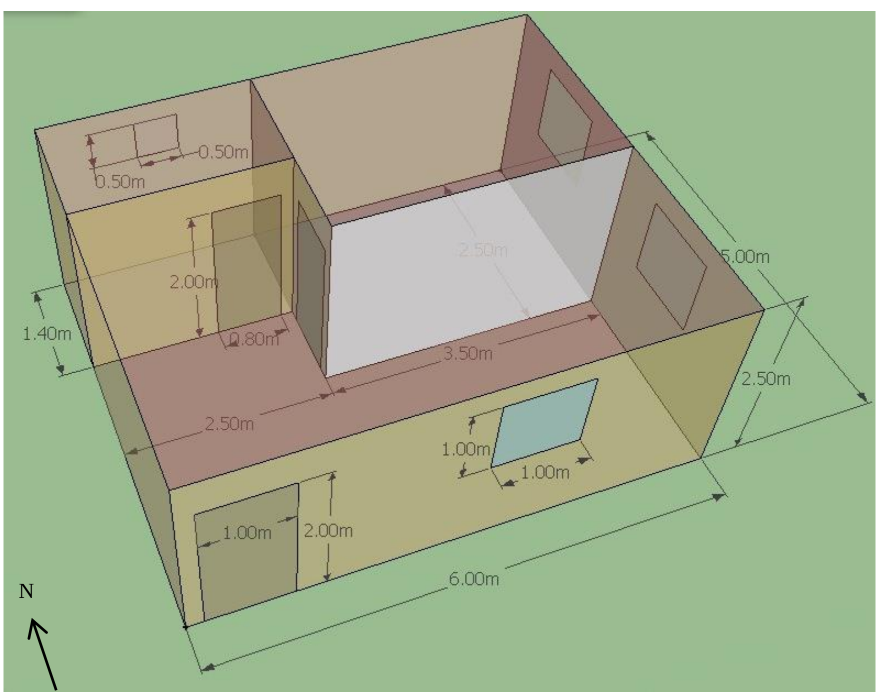

Fig. 5.1. Schematic model of the studied building

Table 5.1. Climate characteristics of Nairobi

Weather file	IWEC, WMO 637400	Heating degree days (base 18 ºC)	305
Latitude / deg	S 1° 19'	Highest average monthly temperature / ºC	20.8
Longitude / deg	E 36° 55'	Lowest average monthly temperature / ºC	16.7
Elevation / m	1624	Köppen classification	Cwb (subtropical highland variety of Oceanic climate)
Cooling degree days (base 25 ºC)	67	ASHRAE climate zone	3A (warm-humid)

Table 5.2. Construction details of the studied building

Construction	Layer (Exterior to interior)	Thickness / mm	U-value / $W \cdot m^{-2} \cdot K^{-1}$
Exterior wall and roof		92	0.445
	Glass fiber laminate	1	
	Extruded polystyrene foam	80	
	Glass fiber laminate	1	
	Gypsum plaster	10	
Floor		87	0.445
	Glass fiber laminate	1	
	Extruded polystyrene foam	80	
	Glass fiber laminate	1	
	Hardwood flooring	5	
Internal walls		102	0.44
	Gypsum plaster	10	
	Glass fiber laminate	1	
	Extruded polystyrene foam	80	
	Glass fiber laminate	1	
	Gypsum plaster	10	
Window		32	2.67
	Clear glazing	8	
	Air gap	18	
	Clear glazing	6	
Door	Wooden door	30	5

5.3.2 Energy demand

Internal gains from lighting, home appliances and occupants are notable elements in indoor thermal balance of the building. These gains contain sensible (convective plus radiative) and latent heat. In this study, two scenarios of basic needs and ordinary needs were defined for home appliances based on the outcomes of former studies (Nzia, 2013; Fabini et al., 2014) that have investigated penetration level of home appliances in urban and rural areas of Nairobi. In designing a PV system, it is important to assess not only energy demand but also temporal distribution of load profiles (Celik, 2007). Consequently, for each zone, internal gains consisting of occupants and home appliances were defined with a daily schedule recurring all days of year as set out in Table 5.3. Power of home appliances and lights were selected based on commercial products and evaluation of former studies (Sigarchian et al., 2015; Kapsalaki et al., 2012). Moreover, fraction radiant and metabolic rate of different activities of occupants were defined based on American Society of Heating, Refrigerating and Air conditioning Engineers (ASHRAE) handbook of fundamentals (2013).

Table 5.3. Internal gains of the studied building for both basic needs and ordinary needs scenarios

Thermal zone	Daily schedule	Type of internal gain	Activity level per person or power / W	Basic needs scenario	Ordinary needs scenario
Living room	7–8 and 18-23	4 People sitting	108	✓	✓
Living room	7–8 and 18-23	Lighting	24	✓	✓
Living room	7-8	Charging cellphone	5	✓	✓
Living room	18-19	Laptop	60		✓
Living room	18-19	Charging flashlight	40	✓	✓
Living room	19-21	Electric cooker	400	✓	✓
Living room	21-23	TV	140		✓
Living room	23-24	Washing machine	370		✓
Living room	24-7	Water heating	300		✓
Living room	24 hours	Refrigerator	26	✓	✓
Sleeping room	23-24	4 People reclining	81	✓	✓
Sleeping room	23-24	Lighting	24	✓	✓
Sleeping room	24-7	4 People sleeping	72	✓	✓
Service room	7–8 and 18-23	0.1 Person (average)	126	✓	✓
Service room	7–8 and 18-23	Lighting (average)	2.4	✓	✓

Annual cooling and heating energy demand to keep the indoor air temperature within the recommended range, i.e. between 18 ºC and 25 ºC (Ministry of Public Works Transport and Communications, 2006; Ministry of Economy and Employment, 2013), was calculated annually. In order to this, each of the main thermal zones of the building, i.e. living room and sleeping room, was supplied by cooling and heating air through a variable air volume (VAV) terminal unit to provide conditioned air when meeting the specified temperature range (DoE, 2013a, 2013b). VAV systems have been widely adopted in recent years due to their high efficiency (Zhang et al., 2015). Table 5.4 provides details of the supplied cooling and heating air with infinite capacity.

Table 5.4. Location and weather data of the studied building

Factor	Value	Unit
Maximum heating supply air temperature	50	ºC
Minimum cooling supply air temperature	13	ºC
Maximum heating supply air humidity ratio	0.0156	kg Water·kg Dry air^{-1}
Minimum Cooling supply air humidity ratio	0.0077	kg Water·kg Dry air^{-1}
Cooling sensible heat ratio (SHR)	0.7	

EnergyPlus ver 8.1 along with *OpenStudio ver. 1.4* were used for calculating annual heating and cooling energy demand. The characteristics of building materials were obtained by dataset of the software or the manufacturer. Within *EnergyPlus*, conduction transfer function (as a sensible heat diffusion technique) combined with effective moisture penetration depth (as an inside surface moisture storage) was selected as heat and moisture transfer technique for surface assemblies of the building. Moreover, an integrated analytical solution was used to calculate zone air temperature and humidity ratios and an adaptive technique categorizing surfaces based on wind and heat flow directions was utilized for calculating exterior convective heat transfer coefficients. Furthermore, Infiltration, i.e. flow of outdoor air into a building through exterior doors, cracks and other unintentional openings (ASHRAE, 2013), was set to 0.6 air changes per hour (ACH) and number of time-steps per hour was set to 60 to run the model at each minute for more accuracy (Corbin et al., 2013; Hong et al., 2008).

5.3.3 Passive cooling

5.3.3.1 Shading

Windows normally have a *U-value* five to ten times higher than wall area (Da Silva et al., 2013) and consequently using shading devices is one of the most effective approaches to decrease cooling energy demand in hot climates (Lomanowski and Wright, 2012; Bellia et al., 2013; Aldawoud, 2013; Kim et al., 2012; Nikoofard et al. 2014). Among different types, exterior shading has proved to be significantly effective for this goal (Bellia et al., 2013; Aldawoud, 2013). Therefore, this approach was applied to all fenestration of the studied buildings by placing pull-down roller blinds with thickness of 10 mm, thermal conductivity of 0.1 W·m^{-1}·K^{-1}, solar transmittance of 0.05, solar reflectance of 0.5 and distance of 5 mm to the glazing. The activation of this approach was conditioned to indoor air temperature reaching 24 ºC.

5.3.3.2 Natural ventilation

Natural ventilation through windows is another useful approach to dissipate the daily heat gain in hot climates. In accordance with ASHRAE handbook of fundamentals (2013), combination of wind and stack effects was considered to model natural ventilation for the studied building. The flow driven by wind Q_w (due to the pressure difference) and flow driven by stack Q_s (due to density and temperature difference) were respectively calculated using Eq. (5.1) and (5.2) (ASHRAE, 2013; DoE, 2013a).

$$Q_w = C_w A_o F_s V \qquad \text{Eq. (5.1)}$$

$$Q_s = C_d A_o F_s \sqrt{2g\Delta H_{NPL}\left(\left|T_z - T_o\right| / T_z\right)} \qquad \text{Eq. (5.2)}$$

Total ventilation flow rate Q was calculated via combining both wind and stack effects using Eq. (5.3) (ASHRAE, 2013; DoE, 2013a). Consequently, whenever the indoor air temperature was above 24 ºC, outdoor air temperature was less than indoor air temperature and outdoor wind speed was less than 20 $m \cdot s^{-1}$, natural ventilation was activated by considering an opening area A_o of 0.05 m^2 for all windows of living room and sleeping room. The size of opening area was adjusted based on the consequent ACH.

$$Q = \sqrt{Q_s^{\,2} + Q_w^{\,2}} \qquad \text{Eq. (5.3)}$$

As former studies (Breesch and Janssens, 2010; Heiselberg et al., 2001; Johnson et al., 2012) suggested, the opening effectiveness C_w and discharge coefficient C_d were not considered constant and respectively calculated using Eqs. (5.4) and (5.5) in accordance with ASHRAE handbook of fundamentals (2013).

$$C_w = 0.55 - \frac{\left|\text{Angle difference}\right|}{180} 0.25 \qquad \text{Eq. (5.4)}$$

$$C_d = 0.40 + 0.0045\left|T_z - T_o\right| \qquad \text{Eq. (5.5)}$$

5.3.3.3 Cool painting

Applying cool (high reflectance and emittance) paints in the façade and roof of buildings is another effective technique to decrease the cooling energy demand in hot climate by reflecting the incident solar radiation away and radiating the heat at night (Dias et al., 2014; Costanzo et al., 2013; Akbari et al., 2001; Zinzi and Agnoli, 2012). Solar absorptance of materials, i.e. fraction of incident solar radiation that is absorbed by the material, characterizes the color of exterior surface (Suehrcke et al., 2008; Costanzo et al., 2014). In this study, applying cool painting to exterior walls and roof was evaluated by decreasing the solar absorptance of the most exterior layer (exterior glass fiber laminate) from the initial value of 0.3 to 0.1, i.e. increasing the solar reflectance from 0.7 to 0.9, based on the results of former studies (Brito Filho et al., 2011; Lapisa et al., 2013). Takebayashi et al. (2016) have pointed out that solar reflectance of cool painted surfaces would decrease rapidly (after 50 days) due to the aging. On the other hand, some scholars have considered even higher values such as 0.95 by Ascione et al. (2010). In this study, the constant value of 0.9 was considered for solar reflectance without analyzing the impact of aging (or assuming repainting).

5.3.3.4 Thickness of interior gypsum plaster

Gypsum plaster has been used for thousands of years in numerous buildings due to advantages such as thermal and moisture buffering, cost, sound insulation and fireproofing (Barbero et al., 2014; Alencar et al., 2011; Berge, 2009). All exterior and interior walls, roof and floor of the studied building are considered coated with interior gypsum plaster with thickness of 10 mm. Subsequently, the thickness was changed to 20 mm to evaluate the impact of interior gypsum plaster on cooling energy demand.

5.3.4 SAPV system

After applying passive cooling techniques and reduction of energy demand, energy supply through SAPV systems was studied for both basic and ordinary needs scenarios. Typical SAPV systems consist of PV array, battery, inverter and charge controller as well as complementary parts such as array mounting structures, cables, switches, fuses, blocking diodes, etc. (Ali and Salih, 2013; AlShemmary et al., 2013; Kalogirou, 2009). To protect PV cells from corrosion, PV cells are connected as a larger unit called PV module. PV modules have different appearance and performance characteristics depending on the manufacturer and type of PV material (Kalogirou, 2009). PV array, consisting of PV modules, supplies power to the load and charges the battery in daytime. Battery in PV system is required for when there is no sunshine (i.e. night and cloudy periods) or PV array cannot supply the load. Therefore, the selection of battery depends on the load and availability requirements. Deep-cycle lead-acid batteries are the most common type being used in PV systems (Kalogirou, 2009). Moreover, as batteries store direct current (DC) and home appliances operate on alternating current (AC), inverter is required to convert the DC to the AC (Kalogirou, 2009). Furthermore, charge controller is used to ensure the protection of batteries from overload and deep discharge. The most common type of charge controller performs on an on/off basis by characterizing two charging and discharging thresholds based on the battery voltage (Ali and Salih, 2013). PV cells have an exponential correlation between the current and voltage (I-V curve) in which there is an optimum point called maximum power point (mpp). Consequently, maximum power point tracker (MPPT) is being used as specific sort of charger controller that converts DC to DC in order to maximize the potential power of PV system. There is a growing interest in using MPPT charger controllers particularly for off-grid power systems (Kalogirou, 2009).

5.3.4.1 Sizing

The first step in designing a PV system is to specify the total energy demand per day based on the load profiles which the system needs to supply (Messenger and Ventre, 2010). The table 5.3 set out the load profiles for both basic and ordinary needs scenarios. Figures 5.2 and 5.3 illustrate how these loads vary during hours of day.

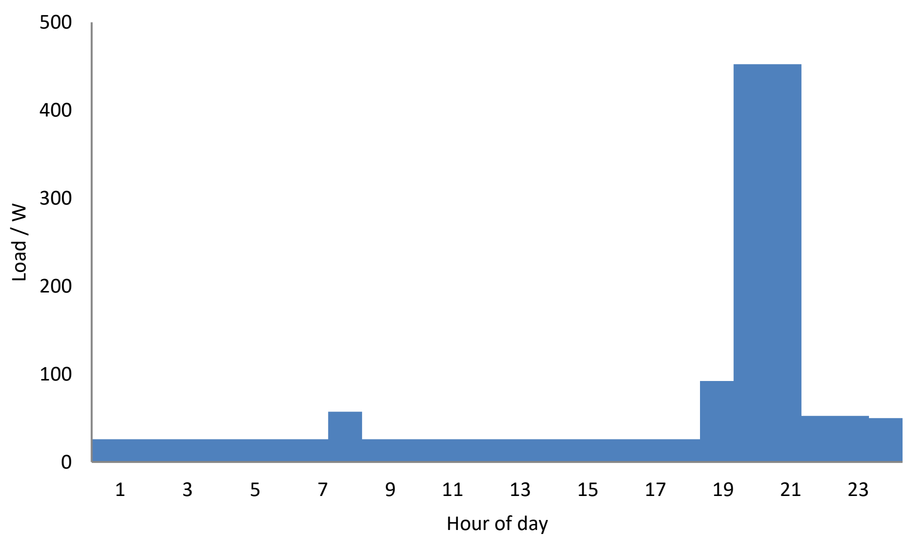

Fig. 5.2. Daily loads for basic needs scenario.

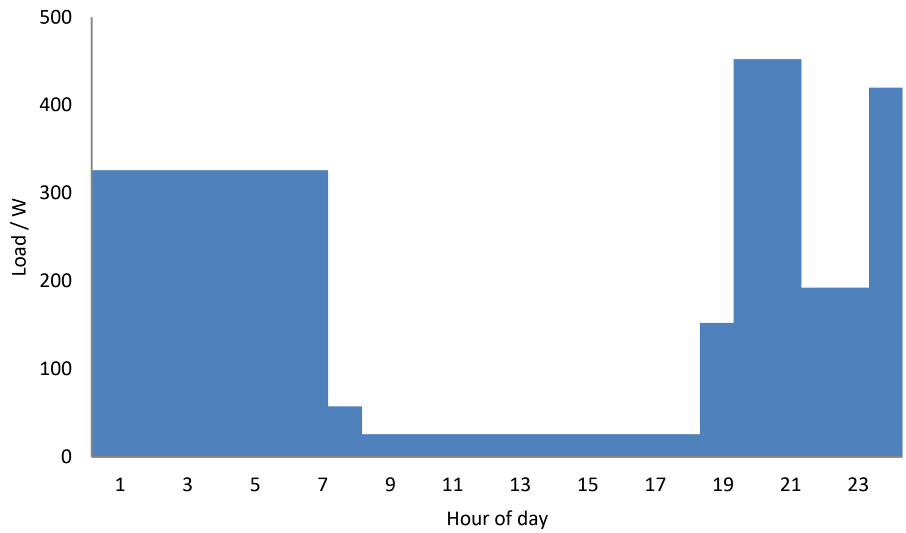

Fig. 5.3. Daily loads for ordinary needs scenario.

As all itemized appliances work with AC, inverter is needed to convert the load to DC. Therefore, the total energy demand per day E_d is related to the losses of the system calculating by Eq. (5.6) (Ali and Salih, 2013; Messenger and Ventre, 2010) where E is energy demand (loads) per day and η refers to the efficiency of the system based on efficiencies of inverter, cable and charge controller.

$$E_d = \frac{E}{\eta} \qquad \text{Eq. (5.6)}$$

The required size of battery is initially calculated through unadjusted capacity C_u, number of autonomy days N_a and the battery voltage V_b. The number of autonomy days depends on several considerations such as number of sequential cloudy days and system application (Ali and Salih, 2013). The voltages of PV array, inverter and charge controller must be in correspondence with each other that is known as system voltage V_{DC} (AlShemmary et al., 2013). Typical SAPV systems use 12 V or 24 V as the system voltage. In this study, N_a was set to 2 and 24 V was selected for V_b. Therefore, C_u was calculated by using Eq. (5.7) (Ali and Salih, 2013).

$$C_u = \frac{N_a \times E_d}{V_b} \quad \text{Eq. (5.7)}$$

Afterwards, adjusted capacity C_a is calculated by taking into account more factors including correction factor F_c to compensate temperature effects, maximum depth of discharge (*DoD*) and η using Eq. (5.8) (Ali and Salih, 2013).

$$C_a = \frac{F_c \times C_u}{DoD \times \eta} \quad \text{Eq. (5.8)}$$

Consequently, by knowing the total required capacity, number of batteries in series and parallel are respectively calculated using Eqs. (5.9) and (5.10) (Ali and Salih, 2013; AlShemmary et al., 2013) where N_{bs} is number of batteries in series, N_{bp} is number of batteries in parallel and C_b refers to the capacity of one battery.

$$N_{bs} = \frac{V_{DC}}{V_b} \qquad \text{Eq. (5.9)}$$

$$N_{bp} = \frac{C_a}{C_b} \qquad \text{Eq. (5.10)}$$

In order to size the PV array, firstly we need to define average solar global horizontal irradiation (GHI) per day for all months of year. Meteorological data provided by NASA (2015) as well as national renewable energy lab (NREL, 2015) were used to obtain this data. Knowing the solar GHI, peak sun hours *PSH* is calculated by considering irradiation of 1 kWh·m^{-2} at each hour (Messenger and Ventre, 2010). Consequently, by defining the least unfavorable month of year, power of the PV array P_{pv} is calculated using Eq. (5.11) (Melby and Cathcart, 2002).

$$P_{pv} = \frac{E_t}{PSH} \qquad \text{Eq. (5.11)}$$

By knowing the P_{pv} and V_{DC}, number of modules in series and parallel are respectively calculated using Eqs. (12) and (13) (Ali and Salih, 2013) where N_{ms} is number of modules in series, N_{mp} is number of modules in parallel, I_{DC} refers to the system current and I_m represents the current of module.

$$N_{ms} = \frac{V_{DC}}{V_m} \qquad \text{Eq. (5.12)}$$

$$N_{mp} = \frac{I_{DC}}{I_m} \qquad \text{Eq. (5.13)}$$

Considering charge controller, its voltage and current need to be defined. As mentioned before, the voltage of the charge controller is equal to the V_{DC}. The rating current of the charge controller must endure short circuit current of the PV array I_{sc}. Considering a safety factor F_{scc}, the current of charge controller I_{cc} is calculated using Eq. (5.14) (Ali and Salih, 2013).

$$I_{cc} = I_{sc} \times N_{mp} \times F_{scc} \qquad \text{Eq. (5.14)}$$

Regarding function of inverter, its input voltage is equal to the V_{DC} and output voltage to the voltage of appliances (240 V in Kenya). The power of inverter P_i must be higher than the maximum power of load P_{max}. Hence, by considering a safety factor F_{si}, the rating power of inverter P_i is calculated using Eq. (5.15) (Ali and Salih, 2013). Ali and Salih (2013) have suggested 1.25 for the F_{si}.

$$P_i = F_{si} \times P_{\max} \qquad \text{Eq. (5.15)}$$

The sizing of SAPV systems is essentially based on the size of PV array and battery (Mellit et al., 2005). However, after defining the required nominal power of PV array and capacity of battery, the performance of the system needs to be evaluated by taking into consideration performance of different segments of the system in correlation with each other. In this study, *PVsyst ver. 6.39* was utilized to assess the SAPV system for the studied building for both scenarios. Apart from the power, the optimum azimuth and tilt angle (inclination) of PV array also need be defined. Considering abundance of solar GHI in summer, the optimization of tilt angle and azimuth were based on winter when the need for solar power was more decisive. Consequently, the impacts of title angle and azimuth on the PV array in winter were assessed. Four PV technologies were selected to be assessed for the designed SAPV system: mono-Si, poly-Si, CdTe and CIS. The specifications of different PV modules are set out in Table B1. Concerning what was discussed in the literature review about variability and liability of cost for PV technologies, the assessment of PV modules in this study was based on the *LLP*, which is defined as the fraction of time when the load cannot be supplied (Celik, 2007; PVsyst, 2015a; McEvoy et al., 2003). Moreover, annual produced energy E_p was evaluated for each PV technology.

3.4.2 Environmental impacts

While power generation from SAPV systems is free from any GHG emissions, their manufacturing is yet questionable from environmental point of view (García-Valverde et al., 2009). Therefore, the GHG emissions associated with the SAPV system GHG_{SAPV} / t of CO_2 was calculated through Eq. (5.16).

$$GHG_{SAPV} = GHG_{PV} + GHG_b + GHG_s \quad \text{Eq. (5.16)}$$

where GHG_{pv} / t of CO_2 is the GHG emissions of the PV modules, GHG_b / t of CO_2 refers to the GHG emissions of the battery and GHG_s / t of CO_2 represents the GHG emissions of the components needed for construction of PV system (balance of system). To assess environmentally friendliness of the proposed SAPV system, the amount of GHG emissions was compared with an alternative grid extension PV systems calculated by Eq. (5.17) (PVsyst, 2015a).

$$GHG_g = L \times E_p \times GHG_{kWh} \qquad \text{Eq. (5.17)}$$

where GHG_g / t of CO_2 is the GHG emissions of the grid extension PV system, L / years is the lifetime of PV system, E_p / kWh refers to the annually produced energy by the SAPV system and GHG_{kWh} / t of $CO_2 \cdot (kWh)^{-1}$ represents the GHG emissions for production of 1 kWh by the grid extension system. The GHG_{kWh} was set to $331x10^{-}6$ t of $CO_2 \cdot (kWh)^{-1}$ with regard to the data for Kenya (PVsyst, 2015b). Moreover, the GHG_b was calculated based on the outcomes of the study by McManus (2012) which suggests 0.9 kg of CO_2 for manufacturing 1 kg of lead acid batteries. The GHG_{pv} and GHG_s were calculated based on the *PVsyst* dataset for different PV technologies. By subtracting the GHG_{SAPV} from GHG_g, reduction in GHG emissions during lifetime through use of SAPV system was calculated for studied PV technologies. The considered lifetimes for the system components were based on the suggestions of former studies: 25 years for the PV array (Jordan and Kurtz, 2013; Mundada et al., 2016; Shouman et al., 2016), 9 years for the battery (PVsyst, 2015b) and 10 years for the other components of balance of system (Zeyringer et al., 2015; AHK Kenya, 2013). Consequently, considering 25 years of assessment, two replacements of the system components (Battery, inverter, charge controller, cables and wires, etc.) were considered in the calculations.

3.4.3 Economic analysis

Levelized Cost of Energy (LCOE) is a reliable and effective criterion for comparing alternative energy production technologies that allows us to obtain the cost per energy unit (Edalati et al., 2016; Silva and Hendrick, 2016). This parameter is considered as the most important parameter in economic analysis of PV systems (Kang and Rohatgi, 2016). It is basically defined as the ratio of discounted value of total cost to the discounted value of total lifetime energy output and is calculated through Eq. (5.18) (Silva and Hendrick, 2016).

$$LCOE = \frac{\sum_{n=0}^{L}\left(\frac{C_n}{(1+d)^n}\right)}{\sum_{n=0}^{L}\left(\frac{E_p}{(1+d)^n}\right)} \qquad \text{Eq. (5.18)}$$

where $LCOE$ / \$·(kWh)$^{-1}$ is the levelized cost of energy, C_n / \$ is the total cost in year n and d is the real discount rate. The lifetimes that were presented in section 3.4.2 were also considered for economic analysis by taking into account the required replacements of components. The costs of different PV technologis were obtained from the manufacturer (Efacec, 2016), namely 0.63 \$·W_p^{-1} for Mono-Si and Poly-Si, 0.55 \$·W_p^{-1} for CdTe and 0.54 \$·W_p^{-1} for CIS. The costs of components of balance of system (battery, inverter, charge controller, cables and wires, etc.) were obtained from commercial products and results of the study by Zeyringer et al. (2015). For the first year, the E_p / kWh was determined by simulation in *PVsyst* and for following years, annual degradation rate of 0.5 % for Mono-Si and Poly-Si and 1 % for CdTe and CIS were applied as suggested by Jordan and Kurtz (2013). Moreover, the real discount rate of 8 % was considered for implemention of the project in Kenya based on the suggestions of AHE kenya (2013) and Pueyo et al. (2016). Using the real discount rate provides a real *LCOE* rather than nominal one as it already has taken into consideration the inflation rate (Reichelstein and Yorston, 2013).

4. Results and discussion

4.1 Passive cooling

Figures 5.4 and 5.5 compare the impact of studied passive cooling techniques on heating and cooling energy demand respectively for basic needs and ordinary needs scenarios. The results highlight the effectiveness of all passive cooling techniques in decreasing cooling energy demand for both scenarios. Natural ventilation proved to be the most effective technique followed by exterior shading, cool painting and increase the thickness of the interior gypsum plaster. Moreover, it is estimated 84.7 % reduction in cooling energy demand by combining all these techniques for the basic needs scenario and 83.3 % reduction for the ordinary needs scenario. While none of these techniques aimed at warming up, cool painting, exterior shading and natural ventilation slightly increase the heating needs. On the other hand, doubling the interior gypsum plaster thickness decreases the heating energy needs mostly by increasing the thermal mass and heat storage of the walls and roof. It must be noted that annual heating energy demand for ordinary needs scenario reached zero. Furthermore, considering that a passive house (International passive house association, 2015) has to have heating and cooling energy demands below 15 kWh·m^{-2}, the combination of selected passive cooling techniques originates a house displaying passive behavior.

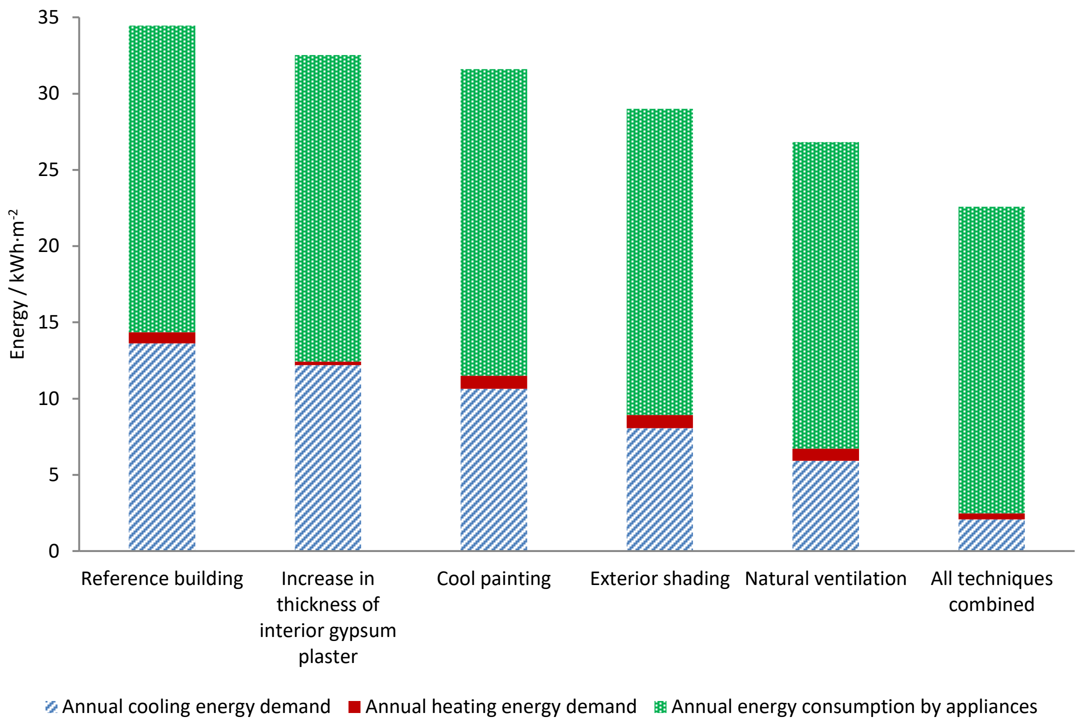

Fig. 5.4. Comparison of impacts of different passive cooling techniques on energy demand (basic needs scenario).

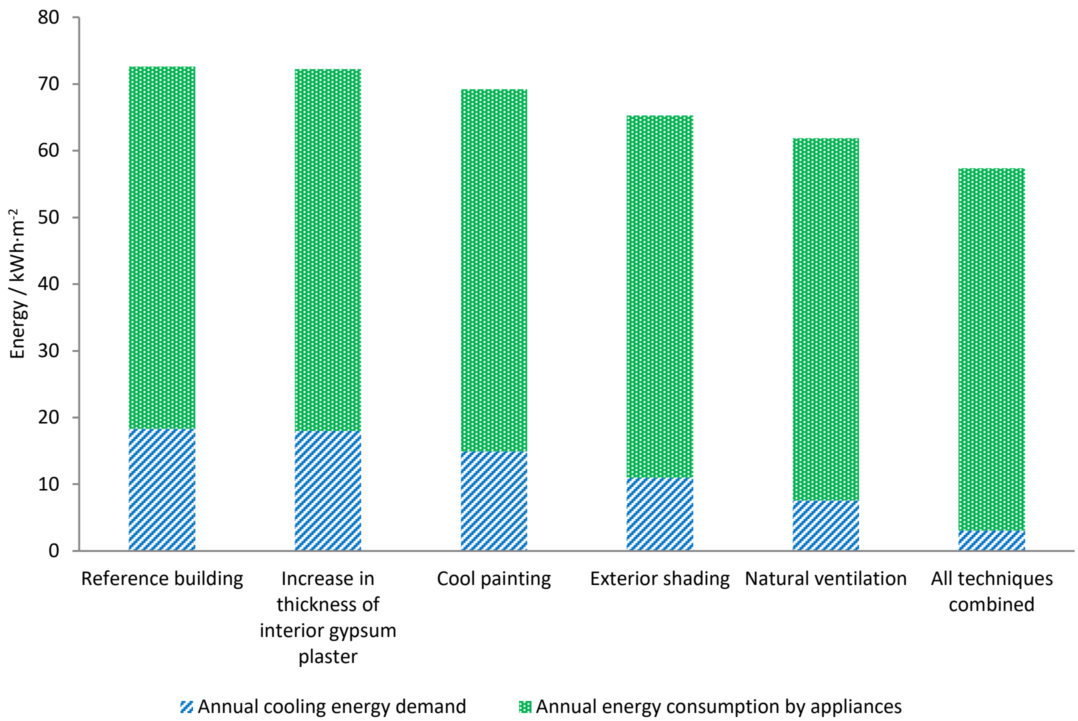

Fig. 5.5. Comparison of impacts of different passive cooling techniques on energy demand (ordinary needs scenario).

5.4.2 SAPV systems

Table 5.5 provides daily average solar GHI as well as clearness index for different months of the year in Nairobi obtained from NASA and NREL databases. While the records from NASA shows notable higher values, the data by NREL was selected for sizing the SAPV system in order to provide more assurance. Hence, the month of July was identified as the least unfavorable month of the year. Former studies (Ondraczek, 2014; Sigarchian et al., 2015; Wasike, 2015) reported daily average solar GHI of 4 kWh·m^{-2} to 6 kWh·m^{-2} in Nairobi. The obtained data from two sources, 4.85 kWh·m^{-2} by NREL and 5.93 kWh·m^{-2} by NASA, differ by 18 %, which result in different SAPV system designs.

Table 5.5. daily average solar GHI and clearness index for different months of the year in Nairobi.

Month	Daily average solar global horizontal irradiation (GHI) / kWh·m^{-2}		Clearness index	
	NASA	NREL	NASA	NREL
January	6.42	5.61	0.630	0.551
February	6.86	5.98	0.655	0.571
March	6.66	5.57	0.633	0.529
April	5.83	4.59	0.575	0.453

May	5.36	4.23	0.562	0.444
June	**5.11**	4.24	0.558	0.463
July	5.23	**4.04**	0.562	0.434
August	5.55	4.19	0.565	0.426
September	6.37	5.18	0.618	0.502
October	6.13	5.13	0.588	0.492
November	5.59	4.45	0.547	0.436
December	6.06	5.04	0.603	0.501
Annual average	5.93	4.85	0.591	0.4835

Figures 5.6 and 5.7 compare the impact of respectively tilt angle and azimuth on global solar on the PV array in winter. The results demonstrate that angle of 25º for tilt angle and azimuth of 0º provide the highest solar absorption for the SAPV system.

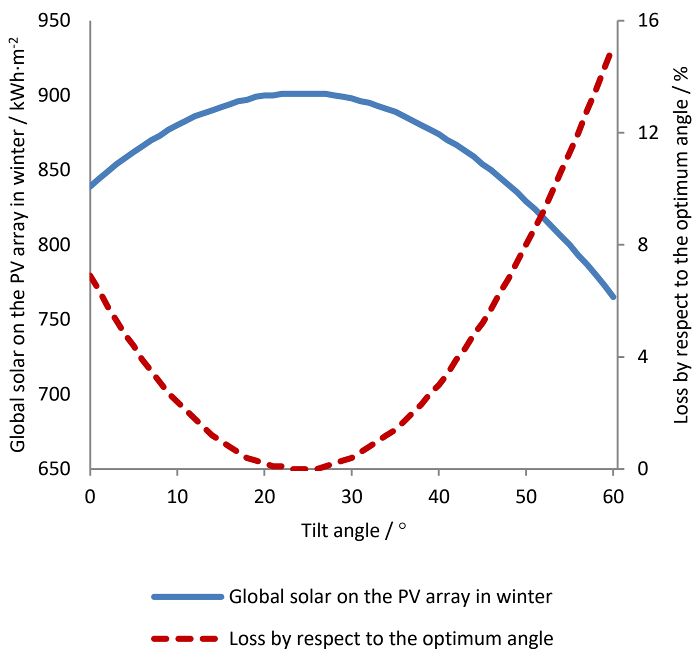

Fig. 5.6. Impact of tilt angle on global solar on the PV array in winter.

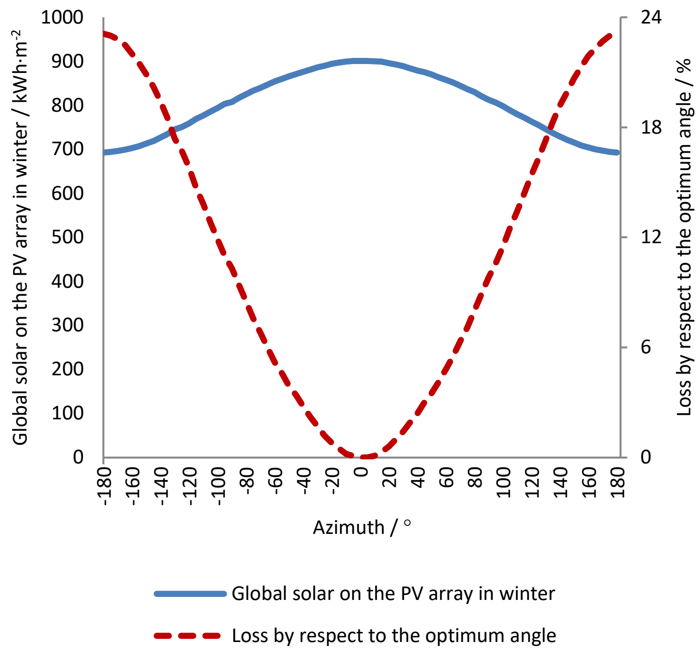

Fig. 5.7. Impact of azimuth on global solar on collector plane in winter.

Regarding capacity of battery, the sizing calculations resulted in 193 Ah for basic needs scenario and 472 Ah for ordinary needs scenario. Consequently, taking into account the safety factor and looking at commercial products, Rolls absorbent glass mat (AGM) type of lead acid battery was selected with capacity of 234 Ah for basic needs scenario and capacity of 592 Ah for ordinary needs scenario. As specifying the exact type of charge controller and inverter is not crucial in sizing of the systems, a generic MPPT charge controller suggested by the software as well as a typical inverter with efficiency of 0.98 were considered in this study.

Figures 5.8 and 5.9 illustrate the impacts of *LLP* and passive cooling techniques on required power of PV array for basic and ordinary needs scenarios, respectively. These results highlight the advantage of integrating demand and supply sides of energy analysis by demonstrating how passive cooling techniques are effective in decreasing the required power of the PV array. Furthermore, the *LLP* proved to have a great impact on sizing of the PV system. There is a sudden increase in the required power of array for the *LLP*s less than 2 % for all passive cooling techniques and scenarios.

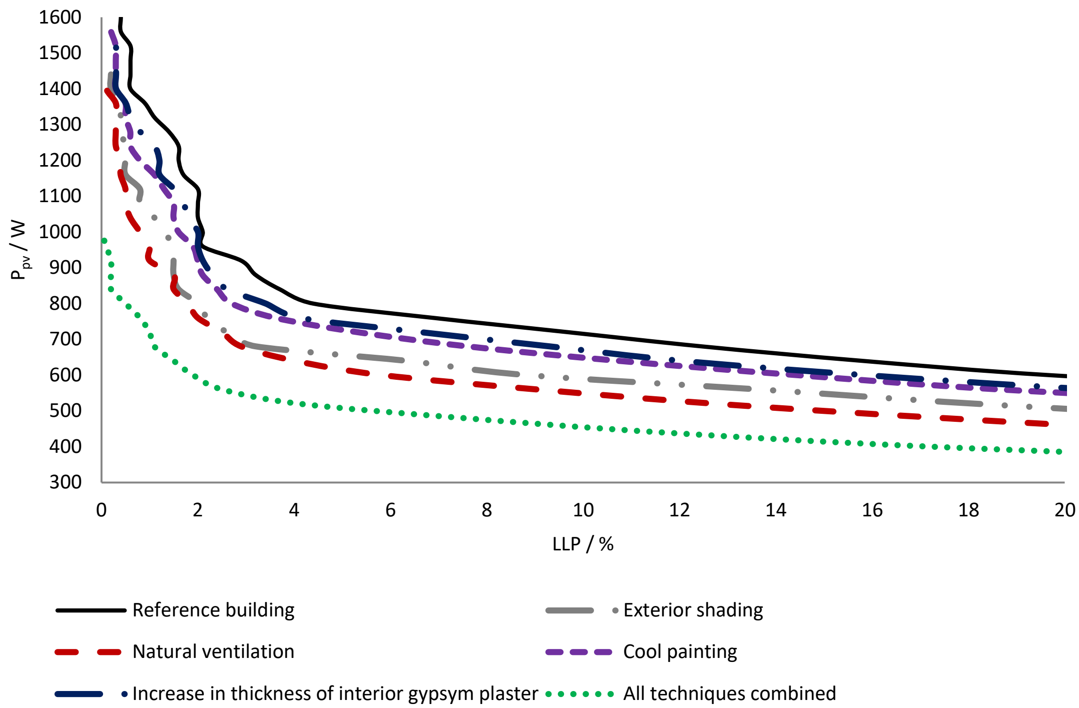

Fig. 5.8. Impacts of *LLP* and passive cooling techniques on the power of PV array for basic needs scenario.

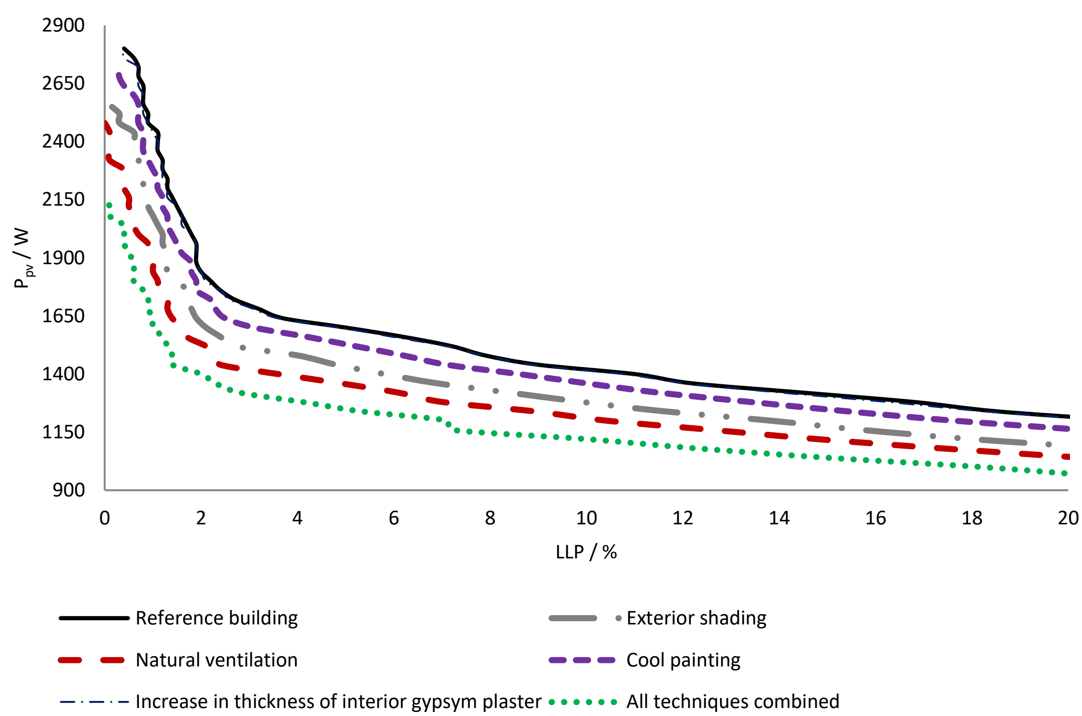

Fig. 5.9. Impacts of *LLP* and passive cooling techniques on the power of PV array for ordinary needs scenario.

Following the results, 600 W was selected as P_{pv} for basic needs scenario and 1700 W for ordinary needs scenario. Tables 5.6 and 5.7 compare the studied PV technologies in terms of *LLP*, *LCOE*, array area, annual produced and energy (E_p) and GHG emissions for basic needs and ordinary needs scenarios, respectively.

Table 5.6. Comparison of studied PV technologies for basic needs scenario.

	Mono-Si	Poly-Si	CdTe	CIS
P_{pv} / W	600	600	600	600
E_p / kWh	958.1	938.4	964.1	1015
Array area / m^2	3.9	6	4.3	4.8
LLP / %	2.3	2.5	2.3	2
GHG_{pv} / t of CO_2	0.918	0.792	0.552	0.180
GHG_b / t of CO_2	0.422	0.422	0.422	0.422
GHG_s / t of CO_2	0.132	0.132	0.132	0.132
GHG_{SAPV} / t of CO_2	1.473	1.347	1.107	0.735
GHG_g / t of CO_2	7.928	7.765	7.978	8.399
Reduced GHG emissions / t of CO_2	6.456	6.419	6.871	7.664
LCOE / $\$\cdot(kWh)^{-1}$	0.183	0.186	0.189	0.174

Table 5.7. Comparison of studied PV technologies for ordinary needs scenario.

	Mono-Si	Poly-Si	CdTe	CIS
P_{pv} / W	1700	1700	1700	1700
E_p / kWh	2723	2667	2742	2862
Array area / m^2	11	16.9	12.2	13.7
LLP / %	1	1.1	1	1
GHG_{pv} / t of CO_2	2.601	2.244	1.564	0.510
GHG_b / t of CO_2	1.447	1.447	1.447	1.447
GHG_s / t of CO_2	0.375	0.375	0.375	0.375
GHG_{SAPV} / t of CO_2	4.424	4.067	3.387	2.333
GHG_g / t of CO_2	22.533	22.069	23.690	23.683
Reduced GHG emissions / t of CO_2	18.109	18.003	19.304	21.351
LCOE / $\$\cdot(kWh)^{-1}$	0.167	0.171	0.168	0.160

Comparing the selected PV technologies and taking into account the *LLP*, CIS demonstrated the best performance followed by CdTe, mono-Si and poly-Si. Nonetheless, the performance of each technology is dependent on the characteristics of specific modules provided by the manufacturer and may vary by using other products. Regarding economic analysis, CIS presented the minimum *LCOE* of 0.167 $\$\cdot(kWh)^{-1}$ followed by 0.175 $\$\cdot(kWh)^{-1}$ for mono-Si, 0.178 $\$\cdot(kWh)^{-1}$ for CdTe and 0.179 $\$\cdot(kWh)^{-1}$ for poly-Si. The average *LCOE* of four studied PV technologies, i.e. 0.173 $\$\cdot(kWh)^{-1}$, is in line with outcomes of the study by Shouman et al. (2016) that obtained 0.17 $\$\cdot(kWh)^{-1}$ for a stand-alone PV system in rural areas of Egypt. It is also less than 0.243 $\$\cdot(kWh)^{-1}$ that was achieved by Zeyringer et al. (2016) for a stand-alone PV system in Kenya. Furthermore, it is far less than the estimated range of 0.35 $\$\cdot(kWh)^{-1}$ to 1.50 $\$\cdot(kWh)^{-1}$ for diesel generators in developing countries (Moner-Girona et al., 2016).

The assessment of environmental impacts associated with the SAPV system compared with a grid extension system presents immense reduction of CO_2 emissions. There is a carbon balance tool featured in the *PVsyst* software for this comparison, but it neglects the environmental impact of batteries. Therefore, results of a former study (McManus, 2012) were utilized to determine the CO_2 emissions of manufacturing lead acid batteries. Taking into consideration the emission of GHG, CIS system has the best performance followed by CdTe, poly-Si and mono-Si, in line with the studies by Carnevale et al. (2014) and by Ito et al. (2010). Actually, CIS cells use a minimal amount of materials which justifies the lower GHG emission needed for manufacturing them. As Peng et al. (2013) have discussed, there is a significant discrepancy in environmental impacts of PV modules from case to case depending on the type, manufacturing process, installation methods and the location. It must also be noted that equivalent CO_2 emissions represents global warming potential (GWP) and does not present total environmental impacts which include others gases such as SO_2, NO_x and CH_4. Furthermore, it is worth stressing that not only emerging PV technologies would reduce the cost of current PV modules, but it is also expected that novel manufacturing methods decrease the environmental impacts associated with their production process.

5.5. Conclusions

This article assessed combination of passive cooling and SAPV system for a pre-fabricated building in rural areas of Nairobi, Kenya. Two scenarios of basic and ordinary needs were firstly defined for typical home appliances. Consequently, annual cooling and heating energy demands to keep the occupants within the comfort temperature (18 ºC to 25 ºC) were calculated. Subsequently, four passive cooling techniques (shading, natural ventilation, cool painting and increased thickness of interior gypsum plaster) were applied to decrease the cooling energy demand. Afterwards, a SAPV system was designed through sizing of the main components (PV array and storage battery) as well as determining the optimum tilt angle and azimuth for the

PV array. Moreover, the impact of *LLP* on required power of PV array was investigated for each passive cooling technique. Finally, four PV technologies (mono-Si, poly-Si, CdTe and CIS) were assessed for the designed SPAV system and compared in terms of environmental impacts and cost. For both basic and ordinary needs scenarios, the SAPV system proved to be a feasible solution with significant lower cost and GHG emissions in comparison with alternative solutions. This work provided a comprehensive approach for electrification of rural areas of Kenya through taking into account both energy demand and supply sides.

The application of all studied passive cooling techniques proved to be effective in decreasing the energy demand. Moreover, a reduction of about 84 % in cooling energy demand by combining all considered techniques originated a house displaying passive behavior. Unlike many of former studies and concerning variability of cost for PV technologies, the sizing of the system was not based on the cost but on the *LLP*. It must be noted that the correlation between energy demand and supply is dynamic and also depends on the wealth of the occupants and on their expectancies. Consequently, considering the huge difference between the required size of the system for supplying either 100 % or 98 % of the time, the optimum size can be established based on the capital cost and level of expectancy of the occupants. The results indicated advantage of considering at least 2 % *LLP* for decreasing the required power of PV array.

The results demonstrated superiority of CIS in terms of energy supply, environmental impact and cost. The results also highlighted dominance of thin films in comparison with the silicon-based modules in terms of energy supply and environmental impacts. Comparing with an alternative grid extension PV system, the SAPV system using CIS modules demonstrated potential reduction of about 21.4 tonnes of GHG emissions for ordinary needs scenario and around 7.7 tonnes for basic needs scenario during its lifetime. Furthermore, this system presented only 18 % of the average *LCOE* of the main alternative for rural electrification in Kenya, i.e. diesel generators.

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Portuguese National Strategic Reference Framework (QREN), through the European Regional Development Fund (ERDF).

Appendix B

Table B1. Characteristics of studied PV technologies (PVsyst, 2015b)

PV Technology	mono-Si	poly-Si	CdTe	CIS
Manufacturer	Ecosol PV tech	Photowatt	First Solar	Hulk Energy
Efficiency / %	18.08	12.48	14.16	N/A
Nominal power of module / W	100	100	100	100
Tolerance in Power / %	±3	±5	±5	±2.5
P_{mpp} / W	100.2	101.1	100.0	99.9
V_{mpp} / V	18.7	16.4	69.9	54.4
I_{mpp} / A	5.36	6.15	1.43	1.84
I_{sc} / A	5.70	6.70	1.57	2.10
V_{oc} / V	22.9	21.3	87.6	73.0
Area of module / m^2	0.646	0.993	0.720	0.805
Weight of module / kg	8.50	12	12	12.90

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CHAPTER 6 LIFE CYCLE COST ANALYSIS

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Abstract

Life cycle cost analysis (LCCA) is a tool to assess the costs associated with each phase of the building life cycle. This article evaluates the life cycle cost (LCC) of a pre-fabricated fiber-reinforced composite (FRC) building in comparison with a masonry one. The four life cycle phases of construction, operation, maintenance and demolition are taken into consideration and the buildings are analyzed in the American cities of El Paso, Los Angeles and San Francisco. The contribution of different building components in construction cost is firstly defined. Consequently, the operation costs to supply cooling and heating energy demands as well as lighting and home appliances are calculated. After determining the maintenance and demolition costs, the total LCC of both building types are compared through net present value (*NPV*). Finally, sensitivity analyses are carried out to assess the impact of influential parameters. The results highlight the significance of construction cost for both structures and higher maintenance and lower demolition costs of the pre-fabricated building. Moreover, higher cooling cost of the pre-fabricated building despite lower *U-value* is highlighted. The pre-fabricated building shows higher total LCC in all locations. The results also demonstrate the importance of location by indicating substantial variations of construction, maintenance and demolition costs among the studied cities. Furthermore, the pre-fabricated building has less operation costs in Los Angeles and San Francisco while it is higher in El Paso. The sensitivity analyses show significant impacts of discount rate and lifetime, moderate influence of the inflation rates of maintenance and demolition costs and limited impact of the inflation rate of electricity cost.

Keywords: Fiber-reinforced composite; LCC; Masonry building; Net present value; Off-site construction; Sandwich-structured composite

Notation

C_t	net cash flow at the year t / $
f	inflation rate / %
FC	future cost / $
N	lifetime / years
NPV	net present value / $
PV	present value / $
r	discount rate / %
t	number of year
U-$value$	overall heat transfer coefficient / $W \cdot m^{-2} \cdot K^{-1}$

Abbreviations

ASHRAE	American society of heating, refrigerating and air conditioning engineers
EIA	energy information administration
EPBD	energy performance of building directive
FRC	fiber-reinforced composite
HVAC	heating, ventilating and air conditioning
IECC	international energy conservation code
ISO	international organization for standardization
LCA	life cycle assessment
LCC	life cycle cost
LCCA	life cycle cost analysis
NZEB	nearly zero energy buildings
VAV	variable air volume

Introduction

Many stakeholders participate in the lifespan of a building throughout its life from construction to demolition. While energy and maintenance costs during the operation phase are of concern to the occupants and owners of buildings, respectively, initial investment (construction cost) is the foremost priority of constructors and investors [1-4]. Life cycle cost analysis (LCCA) has been used to assess the costs associated with each phase of a building's life cycle and provide clarity on how the costs are distributed among the stakeholders. Considering the different dimensions of sustainable development and the need for maximizing the benefits in relation to resources consumed, LCCA can contribute significantly to the sustainable development of buildings [1]. Nonetheless, LCCA is not often applied in Europe or United States [3,5]. Cabeza *et al.* 2014 [6] have conducted a comprehensive review on several Life cycle assessments in the building sector and only highlighted one LCCA among all.

The energy performance of building directive (EPBD) mandates all European countries to achieve nearly zero energy buildings (NZEB) by the end of 2020. In the United States, the executive order on federal leadership on environmental, energy, and economic performance mandates all new federal buildings to achieve zero-net-energy by 2030 [2]. Therefore, this requires designers to implement cost-effective, energy-efficient design practices. Pre-fabricated buildings have been shown to be energy-efficient and therefore have lower energy consumption and environmental impacts [7,8]. Moreover, benefits such as rapid construction, minimal handling, improved surface quality, and less waste have resulted in growth of pre-fabricated (off-site) construction [9,10]. There is also an increasing interest in the use of composite wall systems in pre-fabricated buildings due to advantages such as lower weight and better health and safety for workers [10]. Thus, pre-fabricated composite buildings are being proposed as suitable sheltering and housing solutions.

In a former study [11], technical requirements of a fiber-reinforced composite (FRC) wall system were assessed and it was demonstrated that it can be considered as a novel building material. Moreover, evaluations of environmental impacts [11,12] highlighted its lower embodied impacts (associated with the materials and construction) in comparison with masonry building materials. Thermal analysis of a building design using the proposed materials [13] also showed that it can provide thermal comfort for the occupants in hot climates. In this study, we assess the life cycle cost (LCC) of this building in comparison with a comparable masonry structure. Toward this aim, four main phases of the life cycle (construction, operation, maintenance and demolition) were taken into consideration for buildings located in three American cities: El Paso, Los Angeles, and San Francisco. At the construction phase, quantities of different building components in the construction cost were identified for each building. Then, the operation costs to supply cooling and heating energy demands as well as lighting and home appliances were calculated. Subsequently, the maintenance costs were determined with regard to the life expectancy of different components and the required replacements. Finally, the demolition costs at the end of the life cycle were identified for each building. By discounting the future investments into the current point of time, the LCCs of both buildings were calculated. The study also examines the sensitivity of influential parameters such as discount rate, inflation rate of electricity, maintenance and demolition costs, as well as lifetime on the LCC of building. This study represents the first analysis of the life cycle cost-effectiveness of pre-fabricated FRC buildings in comparison with a conventional building strategy.

Literature review

The use of the term "costs-in-use" in the UK in the late 1950s is considered the starting point of analyzing operational costs instead of capital costs by themselves. LCC, however, was developed in the mid-1960s by the US Department of Defense. In 1973, the energy crisis led to a keen interest in use of LCC in the building industry and continous efforts toward considering future costs during building design [14]. In 2000, the ISO 15686-1 standard [15] defined principles of whole life cycle costing considering different phases of a building's life. Building LCC standards [16,17] define four main phases of the building life cycle: construction, operation, maintenance, and demolition. However, the literature includes studies that contain a range of life cycle phases. For instance, while Lee *et al.* 2015 [2] have only considered construction and operation costs in their LCCA, other studies have included maintenance [1,3,18-28], demolition [1,18,19,23,25,27,28] and transportation [18,25] costs. Moreover, the scope of costs within each life cycle phase can vary from one study to another. For instance, Heralova 2014 [3] included the costs related to design, preliminary engineering support, and surveying in the construction cost, and the costs of cleaning, administration, and insurance in the operation cost, which are not often considered in LCCA. Han *et al.* 2014 [18] and Kovacic and Zoller 2015 [1] have compared the coverage of different phases in LCCA of commercial software used for building cost estimation.

Former studies on the LCCA of buildings do not agree on the most dominant phase. For instance, Islam *et al.* 2015 [19] identified construction as the phase with the highest costs followed by maintenance, operation, and demolition. Similarly, Heralova 2014 [3] and Atmaca and Atmaca 2016 [23] identified construction as the most dominant phase. On the other hand, Han *et al.* 2014 [18] found that operational costs become more significant when the building has a lifespan of more than 30 years.

Cabeza *et al.* 2014 [6] have highlighted the importance of lifetime in life cycle assessment (LCA) studies, noting variation from 10 to 100 with 50 years as the most common value. Lee *et al.* 2015 [2], Kovacic and Zoller 2015 [1], Islam *et al.* 2015 [19], Gurung and Mahendran 2002 [25] and Marszal *et al.* 2012 [27] also have recommended 50 years as the proper lifetime for LCCAs of buildings. However, Lee *et al.* 2015 [2] and Chiang *et al.* 2015 [29] believe that 50 years is not sufficient and considered respectively 60 and 75 years. On the other hand, Heralova 2014 [3] has claimed that while 25 to 30 years may be suitable for public buildings, this number should reduce to 10 to 12 years for private investors. Moreover, Stocker *et al.* 2015 [4], Ferreira *et al.* 2014 [24] and Matic *et al.* 2015 [30] have considered 30 years for identifying the cost-optimal renovation/retrofit solution. Kaziolas *et al.* 2015 [26] have chosen 20 years for optimization of a timber building and Atmaca and Atmaca have selected 15 years for LCCA of temporary housing solutions. This variation of lifetimes in the literature suggests it is worthy to explore in LCAs and LCCAs.

Net present value (*NPV*) is the most common metric in LCCA studies [1,3,4,7,18-20,24,30], while other metrics such as value for money [2], internal rate of return [20], payback period [30], cost-benefit analysis [22], and saving to investment ratio [21] have also been utilized. Sensitivity analysis has been highly recommended in different studies by varying factors such as lifetime [3,20,21,23,25], discount rate [1,3,22,24,25], inflation rate [4,7,18,22,24,27], investment cost [4,27,28] and the database [1]. While most research on LCCA of buildings have located the studied building(s) in one city [1-3,7,18,19,21-30] or a region [4], and therefore only considered one climate type, Kniefel 2010 [20] has investigated various climate types. The climate type has substantial impacts on the required energies for heating, ventilating, and air conditioning (HVAC) and their consequent operational costs. Furthermore, material, labor, and equipment costs can vary in different locations.

Previous LCCAs have studied different types of buildings such as residential [19,22,26,29], multi-residential [2,24,27,28,30], office [1,7,18], temporary housing [23], and public [3,4,21]. LCCA has mainly been used in retrofit and renovation studies for finding the cost-optimal design of walls [2,3,7,18,22,24,26,30], windows [18,22,24,26,30], roof [3,19,24,26,30], floor [19,24,26,30], HVAC [4,7,18,22,26,30], and renewable energy source [7,26-28] by examining different forms of buildings such as masonry [2,3,7,18,19,22,24], modular [27,28] and pre-fabricated [30]. These studies are mainly focused on comparison of different design strategies for a single type of building and there are relatively few comparative studies analyzing LCC of different buildings. For instance, Kneifel 2010 [20] has compared different commercial buildings to evaluate the life cycle cost-effectiveness and carbon emissions of each design. Moreover, Atmaca and Atmaca 2016 [23] have compared LCCs of prefabricated and container housing as two types of post-disaster temporary housing solutions. Similarly, Gurung and Mahendran 2002 [25] have compared LCC of a new steel portal frame building incorporating composite sandwich panel with those of a conventional building system. Ilg *et al.* 2016 [31] have performed a comprehensive review on the use of FRC in infrastructures and pointed out its vast use in bridge structures. To our knowledge, none of the former studies have investigated the LCC of FRC buildings. Therefore, comparing LCC of these buildings as modular and pre-fabricated sheltering and housing solutions with masonry buildings can bring insights into their cost-effectiveness in different life cycle phases.

LCCA Methodology

Reference building

The reference building is a 30 m^2 one-story sheltering and housing solution designed for a single-family consisting of four people. It comprises one living room, one sleeping room, and a bathroom as shown in Fig. 6.1. In this study, the building was placed in three locations: El Paso (Texas, United States), Los Angeles (California, United States) and San Francisco (California, United States). Table 1 shows characteristics of these three climates. The selection of these locations was to assess the influence of following items:

1) Climate: While all selected cities are categorized as zone 3 in the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) climate zones, El Paso and Los Angeles represent sub-category of 3B (dry) and San Francisco is classified as sub-category of 3C (warm). This selection allows us to compare the impact of climate zone sub-category on the operation cost.

2) Geographical location: How influential are the variations of material, labor and equipment costs among different cities and electricity cost among different states?

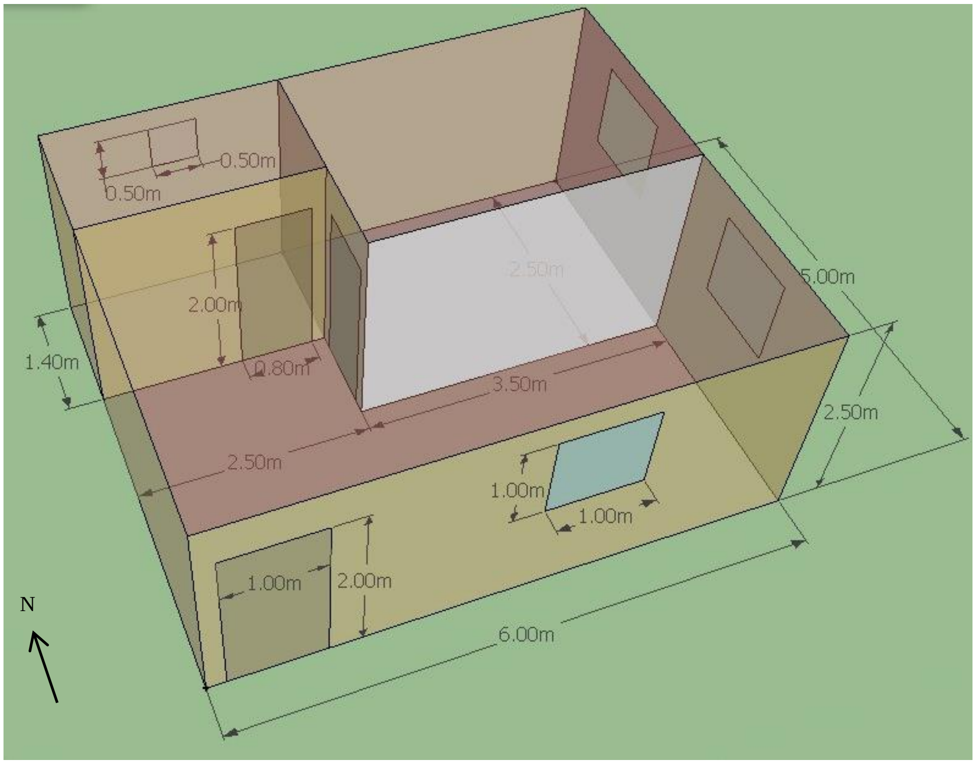

Fig. 6.1. Schematic model of the studied building

Table 6.1. Characteristics of climates in energy simulations

Location	El Paso, TX, United states	Los Angeles, CA, United states	San Francisco, CA, United states
Weather file used for simulation in EnergyPlus	TMY3, WMO 722700	TMY3, WMO 722950	TMY3, WMO 724940
Cooling degree days (base 25 ºC) [32]	620	20	9
Heating degree days (base 18 ºC) [32]	1283	750	1571
ASHRAE climate zone	3B (Dry)	3B (Dry)	3C (Warm)

LCCA

ASTM E917-13 [16] and ISO 15686-5 [17] are two widely used standards that set guidelines for LCCA of buildings. Both standards recommend including four life cycle phases, which were included in this study: construction, operation, maintenance, and demolition. Defining objectives, alternatives and constraints is the first step in any LCCA. The objective of this study is to compare two alternative designs for the reference building. Construction details for the two designs, sandwich-structured composite and masonry, are listed in table 6.2. The design of the sandwich-structured composite (pre-fabricated) was developed in an earlier study [11] and the comparable masonry structure was defined in accordance with the International Energy Conservation Code (IECC) [33]. The whole building was considered as the functional unit of analysis. However, differences between the two designs are limited to the main structural components and do not include finishing and decorative items.

Table 6.2. Construction details of the studied building

Building component	Sandwich-structured composite (Pre-fabricated)			Masonry		
	Layers (Exterior to interior)	Thickness / mm	*U-value* / W·m⁻²·K⁻¹	Layers (Exterior to interior)	Thickness / mm	*U-value* / W·m⁻²·K⁻¹
Exterior walls		102	0.439		370	0.627
	Glass fiber laminate	1		Gypsum plaster	15	
	Extruded polystyrene foam	80		Brick	150	
	Glass fiber laminate	1		Air	50	
	Gypsum plaster	20		Polyurethane	30	
				Brick	110	
				Gypsum plaster	15	
Roof		102	0.439		280	0.690
	Glass fiber laminate	1		Roof membrane	10	
	Extruded polystyrene foam	80		Polyurethane	30	
	Glass fiber laminate	1		Light Concrete	100	
	Gypsum plaster	20		Reinforced concrete slab	130	
				Gypsum plaster	10	
Floor		102	0.439		250	2.500
	Glass fiber laminate	1		Poured concrete	100	

	Extruded polystyrene foam	80		Reinforced concrete slab	150	
	Glass fiber laminate	1				
	Gypsum plaster	20				
Internal walls		102	0.439		170	2.273
	Gypsum plaster	10		Gypsum plaster	10	
	Glass fiber laminate	1		Brick	150	
	Extruded polystyrene foam	80		Gypsum plaster	10	
	Glass fiber laminate	1				
	Gypsum plaster	10				
Window			2.67			2.67
	Shading blind	10		Shading blind	10	
	Clear glazing	8		Clear glazing	8	
	Air gap	18		Air gap	18	
	Clear glazing	6		Clear glazing	6	
Door		30	5		30	5
	Wood	30		Wood	30	

LCCA takes into consideration the time value of money. Construction cost takes place at the beginning of the lifespan and consequently is a nominal value, while the costs of the three other phases must be discounted to the nominal time. Net present value, *NPV*, is the value of future investment at the current point of time and is calculated by using Eq. (1) [1,18]:

$$NPV = \sum_{t=1}^{N} \frac{C_t}{(1+r)^t} \qquad \text{Eq. (1)}$$

where t is the number of years, N is the lifetime, C_t is the net cash flow at the year t, and r is the discount rate. As discussed in the literature review, defining N and r is highly influential in LCCA. Based on the recommendations of former studies, N was set to 50 years [1,6,19] and r was set to 6% [19,34] in this study. In addition to the lifetime and discount rate, another influential factor that must be regarded is inflation

[1,19,34]. While construction costs are based on the current available data, increase in costs must be taken into consideration for future costs (operation, maintenance, and demolition), which was calculated by using Eq. (2) [19]:

$$FC = PV \times (1 + f)^t \qquad \text{Eq. (2)}$$

where *FC* is the future cost, *PV* is the present value and *f* is the inflation rate.

Construction costs

The construction costs for both structures were calculated based on the costs associated with the material, labor and equipment, but did not include costs of delivery and markup by contractors. First, the average costs for each category was obtained from the National Construction Estimator database [35] and the *CYPE* software [36]. Afterwards, the costs were adjusted for each of three locations by using area modification factors. The National Construction Estimator [35] suggests modification factors of -3% for material, -22% for labor, and -1% for equipment costs in El Paso. For Los Angeles, the modification factors are +3% for material, +15% for labor, and +1% for equipment costs. It also recommends +3% for material, +58% for labor, and +1% for equipment costs in San Francisco.

Operation costs

Operation costs are mainly due to electricity usage for lighting, home appliances, and air conditioning (heating and cooling). Internal gains consisting of occupants, lighting, and home appliances were assumed with a daily schedule recurring all days of year, as listed in Table 6.3. The fraction radiant and metabolic rate of different activities of occupants were defined in accordance with the ASHRAE Handbook of Fundamentals [37]. Moreover, nominal power consumption of home appliances was selected based on commercial products and results of an earlier study [38].

Table 6.3. Internal gains of the studied building at operation phase

Thermal zone	Daily schedule	Type of internal gain	Activity level per person or power / W [37, 38]
Living room	7–8 and 18-23	4 People sitting	108

Living room	7–8 and 18-23	Lighting	24
Living room	7-8	Charging cellphone	5
Living room	18-19	Laptop	60
Living room	18-19	Charging flashlight	40
Living room	19-21	Electric cooker	400
Living room	21-23	TV	140
Living room	23-24	Washing machine	370
Living room	24-7	Water heating	300
Living room	24 hours	Refrigerator	26
Sleeping room	23-24	4 People reclining	81
Sleeping room	23-24	Lighting	24
Sleeping room	24-7	4 People sleeping	72
Bathroom	7–8 and 18-23	0.1 Person (average)	126
Bathroom	7–8 and 18-23	Lighting (average)	2.4

Annual cooling and heating energy demands to keep the indoor air temperature within the recommended range (between 18 ºC and 25 ºC [39,40]) was calculated annually. In order to cool down the building in summer, two passive cooling techniques were applied: Exterior shading to decrease the heat gain and natural ventilation (free cooling) to dissipate the daily heat gain. A shading blind with thermal conductivity of 0.1 $W{\cdot}m^{-1}{\cdot}K^{-1}$ and distance of 5 mm to the glazing was selected for the exterior shading and combination of wind and stack effects were considered to model natural ventilation with regard to the ASHRAE Handbook of Fundamentals. Further details about the characteristics and activation of shading and natural ventilation can be found in an earlier study [13]. *EnergyPlus ver 8.1* as well as *OpenStudio ver. 1.4* were used for this calculation and the specifications of building materials were obtained from datasets in the software or from the manufacturer. Within *EnergyPlus*, the conduction transfer function was selected as the heat transfer technique for surface assemblies of the building. An integrated analytical solution was utilized to calculate zone air temperature and humidity ratios. Moreover, an adaptive technique classifying surfaces based on wind and heat flow directions was used for calculating exterior convective heat transfer coefficients. Furthermore, infiltration of the building was set to 0.6 air changes per hour and the number of time-steps per hour was set to 60 to run the model at each minute for more accuracy [41,42]. To calculate the energy demands, each of the main thermal zones of the building (living room and sleeping room) was supplied by cooling and heating air by a variable air volume (VAV) terminal unit to supply conditioned air when meeting the discomfort temperature range [43,44].

After calculating the annual energy demand for lighting, home appliances, heating, and cooling, the cost of the operation phase was calculated based on cost data by the United States Energy Information Administration (EIA) [45]. The cost of electricity (as of February 2016) is 11.06 cents per kWh in Texas and 17.69 cents per kWh in California. According to the EIA, electricity costs in the United States have increased 0.5% per year over last decade. Thus, this rate was selected as the inflation rate for operation costs.

Maintenance and demolition costs

In order to determine the maintenance costs, life expectancy of building components must be defined. The life expectancy of the sandwich-structured composite, doors, and windows are 30 years, while the masonry components are one of the most durable building components, lasting for the entire lifetime (50 years) [46]. As this study does not take into account finishing and decorative items, the maintenance costs are mainly for the replacement (reconstruction) of composite components, as well as doors and windows after 30 years.

Demolition costs consisted of labor and equipment costs. The average costs for each category were obtained from the National Repair and Remodeling Estimator [47] and *CYPE* software [36], and adjusted for the three locations by using the same area modification factors mentioned in the construction costs section. Defining the inflation rate for construction industry is challenging as it depends on numerous factor. In this study, the inflation rate of maintenance and demolition costs was set to 3.6% per year based on the Turner building cost index [48].

Sensitivity analysis

The assumptions for the discount and inflation rates and lifetime have significant impacts on the LCC [1,6,49]. Considering the uncertainty regarding these parameters, sensitivity analyses are performed to assess the magnitude of these effects. In this study, the four parameters of discount rate, inflation rate of electricity cost, inflation rate of maintenance and demolition costs and lifetime were considered for sensitivity analysis. Variations of ±3 % for the discount rate, ±1.5 % for the inflation rate of electricity cost, ±1.8% for the inflation rate of maintenance and demolition costs and ±20 years for the lifetime were assumed and examined for both types of structure in El Paso. It should be noted that the three studied locations have different materials, labor, equipment cost (related to the construction costs) as well as electricity cost and the climate (related to the operation costs). Therefore, locating the studied building in these cities also provides the possibility to assess the influence of such parameters and can be included as a sensitivity analysis.

Results and discussion

Construction costs

Fig. 2 shows the shares of building components in the construction costs of the pre-fabricated and masonry buildings located in El Paso. As the same materials and specifications were considered for the doors and windows, their construction costs are equal. The results demonstrate that exterior walls have the highest contribution to the construction costs for both structures. Moreover, while the foundation and roof of the masonry structure required higher construction costs, the costs of floor and interior and exterior walls were higher for the pre-fabricated structure.

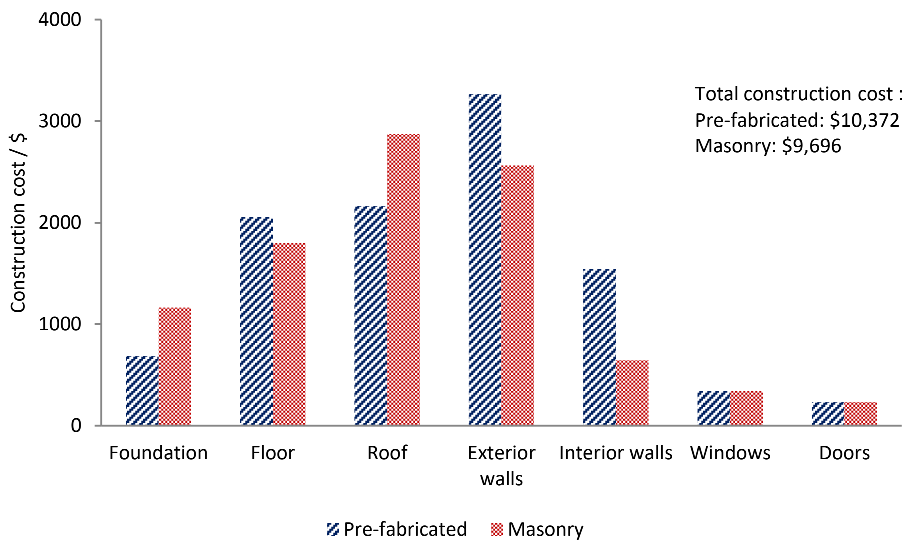

Fig. 2. Share of different components in the construction costs of pre-fabricated and masonry buildings in El Paso

Operation costs

Table 4 compares the annual and life cycle operation costs of the pre-fabricated and masonry buildings in the three studied locations. The differences between costs in different locations are due to the different cost of electricity for end-use customer as well as required energies for cooling and heating. These results show that both cooling and energy costs are relatively small for both structures. Due to the lower *U-value* of the pre-fabricated structure in comparison with the masonry one, heating energy cost is lower in all locations. By contrast, cooling energy cost is higher for the pre-fabricated building. This can be explained by high solar gains and lower thermal mass and heat transmittance of the pre-fabricated building. Although the pre-fabricated building has lower *U-value*, due to high outdoor air temperature (especially in El Paso) the solar gain through windows still can be significant. Furthermore, higher thermal mass of the masonry building translates into it retaining and dissipating absorbed heat during the night [50]. Therefore, in spite of applying shading and natural ventilation, heat is trapped in the the pre-fabricated building due to its high heat gains and lower thermal mass and *U-value*. Sameni et al. 2015 [51] and Dengel and Swainson 2012 [50] have discussed how overheating can happen in well-insulated airtight dwellings with low thermal mass like the studied pre-fabricated building. Taking into account both cooling and energy demands, the operation cost of the pre-fabricated building is slightly lower than the masonry building in Los Angeles and San Francisco, and higher in El Paso.

Table 4. Operation costs of the pre-fabricated and masonry buildings in the three locations

Location	El Paso		Los Angeles		San Francisco	
Structure	Pre-fabricated	Masonry	Pre-fabricated	Masonry	Pre-fabricated	Masonry
Annual cost for electricity usage of home appliances / $	180	180	288	288	288	288
Annual heating cost / $	10	19	2	9	12	31
Annual cooling cost / $	38	19	5	1	1	0
Annual cost / $	228	217	295	297	302	319
NPV of life cycle operation cost / $	3,874	3,693	5,010	5,050	5,105	5,425

Maintenance and demolition costs

Table 5 compares the maintenance and demolition costs of the pre-fabricated and masonry buildings in the three studied locations. The huge difference between the maintenance costs of the pre-fabricated and masonry building is due to the shorter life expectancy of composite components and the need for replacement after 30 years. By contrast, the demolition cost is higher for the masonry building in all locations. This can be explained by ease of destruction for pre-fabricated structures and the smaller amount of required labor. These results also show significant reduction of future investments when they are discounted to the present value.

Table 5. Maintenance and demolition costs of the pre-fabricated and masonry buildings in the three locations

Location	El Paso		Los Angeles		San Francisco	
Structure	Pre-fabricated	Masonry	Pre-fabricated	Masonry	Pre-fabricated	Masonry
Maintenance / $	27,987	1,898	33,833	2,278	39,395	2,629
NPV of life cycle maintenance cost / $	4,873	331	5,891	397	6,859	458
Demolition cost / $	10,842	19,392	15,895	26,458	21,762	34,558
NPV of life cycle demolition cost / $	998	1,102	1,466	1,508	2,010	1,975

LCC

Fig. 3 illustrates the total LCCs of the pre-fabricated and masonry buildings in the three studied locations. The results demonstrate that for the masonry building, construction cost is the most significant cost followed by operation, demolition and maintenance. For the pre-fabricated building, construction is also the most significant cost followed by the maintenance, operation and demolition costs. Furthermore, maintenance costs are significantly greater for the pre-fabricated building and the demolition cost is higher for the masonry building in all locations.

In comparing the costs of each phase, the influence of discounted values needs to be highlighted. While the construction cost is related to the current point of time and the nominal values are considered for this phase, the operation cost is considered annually throughout the lifespan of the building and maintenance and demolition costs are calculated 30 and 50 years later.

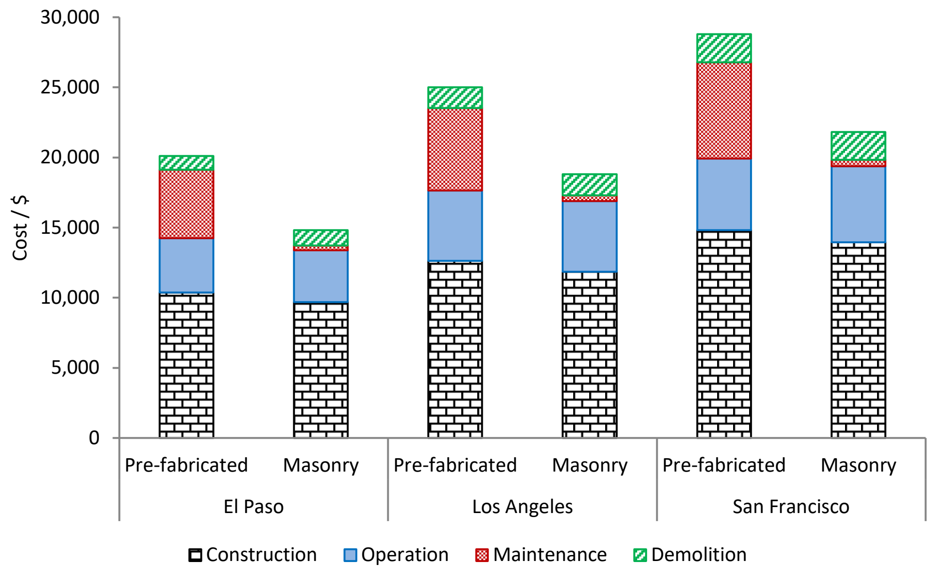

Fig. 3. Total LCCs of pre-fabricated and masonry buildings in the three studied locations

Sensitivity analysis

Fig. 4 compares the impacts of the discount rate on the LCCs of pre-fabricated and masonry buildings in El Paso. The results demonstrate a substantial impact of discount rate on the LCC, especially for the pre-fabricated building. This can be explained by the higher future costs for this structure, such as replacement of pre-fabricated components after 30 years (maintenance cost). As the construction cost is related to the current point of time, variations of discount rate presented no impact. It can also be observed that selecting a higher discount rate reduces the LCCs of both buildings as well as the difference between them. These results imply the importance of selecting a discount rate while using net present values.

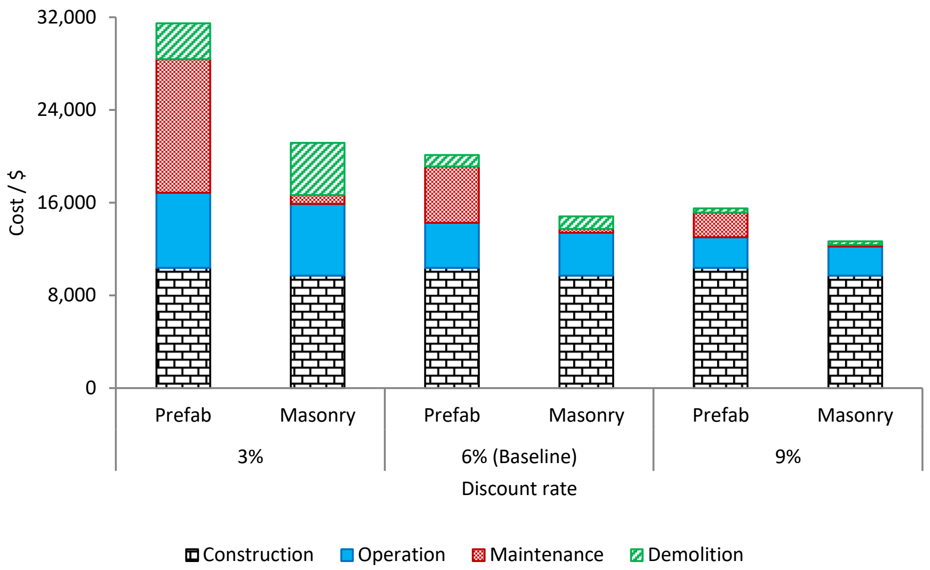

Fig. 4. Impacts of discount rate on LCCs of pre-fabricated and masonry buildings in El Paso

Fig. 5 illustrates the impacts of inflation rate of electricity cost on the LCCs of pre-fabricated and masonry buildings in El Paso. The influence of this parameter is limited to the operation cost and consequently has a less significant effect in comparison with the discount rate. However, for those cases with higher operation costs, the electricity cost inflation rate could be more impactful. The negative inflation rate represents a decrease in electricity cost due to the rapid growth of renewable energy.

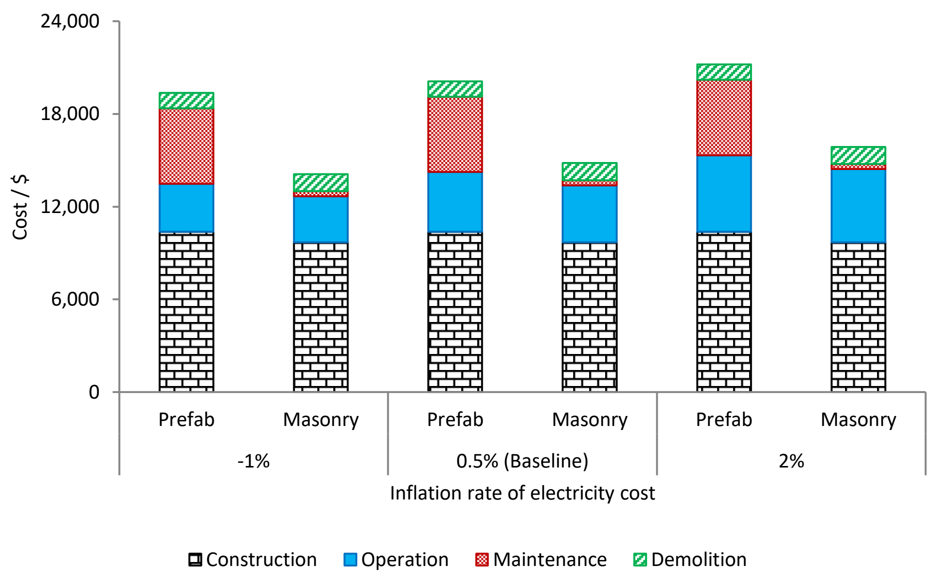

Fig. 5. Impacts of inflation rate of electricity cost on LCCs of pre-fabricated and masonry buildings in El Paso

Fig. 6 shows the impacts of the inflation rate of maintenance and demolition costs on the LCCs of pre-fabricated and masonry buildings in El Paso. As the maintenance cost of the pre-fabricated building is notably higher in comparison with the masonry one, the inflation rate of maintenance cost has more influence on it. Moreover, increasing the inflation rate of demolition cost expands the contribution of demolition phase to total LCC especially in case of the masonry building.

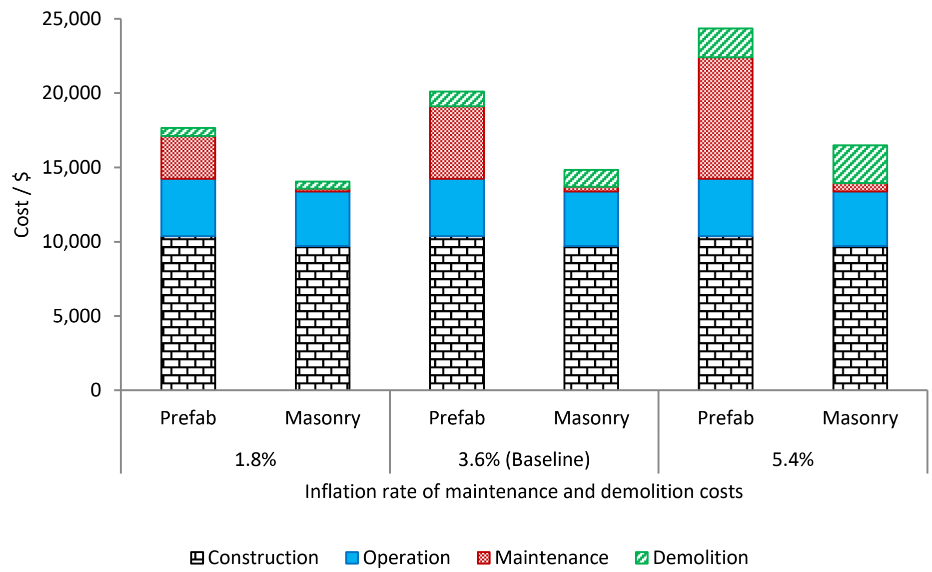

Fig. 6. Impacts of inflation rate of maintenance and demolition costs on LCCs of pre-fabricated and masonry buildings in El Paso

Fig. 7 illustrates the influence of lifetime on the LCCs of the pre-fabricated and masonry buildings in El Paso. These results show that changing the lifetime of analysis is highly influential in LCCs of both buildings. While the LCC of the pre-fabricated building is slightly less than the masonry one for lifetime of 30 years, it is 36 % and 23 % higher respectively for 50 and 70 years of analysis. The life expectancy of the pre-fabricated structure (30 years) has a consequential impact on its higher LCC for 50 and 70 years analyses.

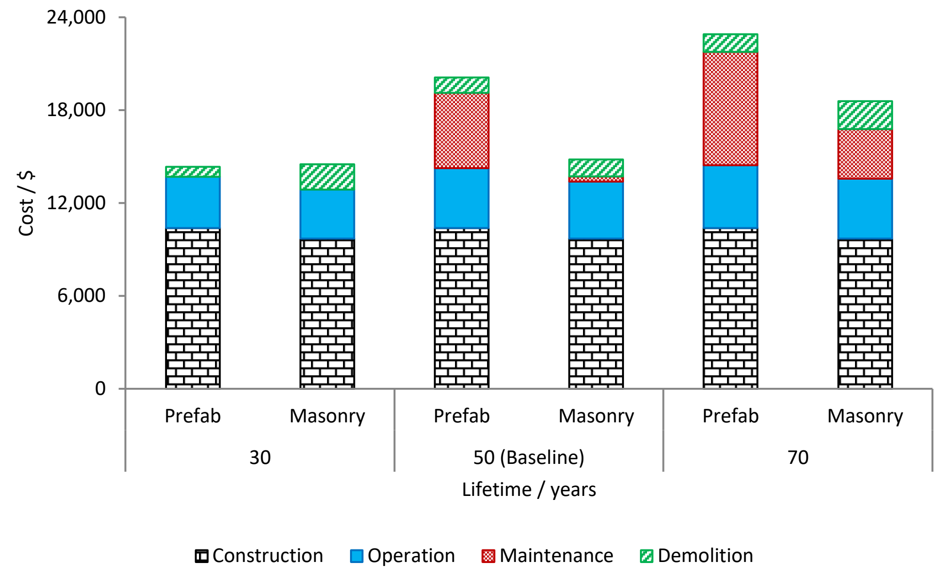

Fig. 7. Impacts of lifetime on LCCs of pre-fabricated and masonry buildings in El Paso

Conclusions

This article assessed the total LCC of a prefabricated building in comparison with a masonry building in different locations. The results point out that for both structures, the exterior walls are the most significant component in construction cost and construction itself is the costliest phase. One interesting finding is that due to high heat gains and airtightness and low thermal mass and *U-value*, the heat can be trapped in the pre-fabricated building in summer and therefore it has higher cooling cost than the masonry one. Furthermore, due to shorter life expectancy of the pre-fabricated structure, its maintenance cost is much higher than the masonry building. On the other hand, the demolition cost of the pre-fabricated building is smaller because of its ease of destruction. Taken together, the pre-fabricated building has higher LCC in all locations. Therefore, future research could usefully explore low-cost components and more economical construction methods for the pre-fabricated building. Moreover, a greater focus on increasing the life expectancy of the FRC components is required to advance its use in the building sector.

Studying different locations allowed us to assess the impacts of climate and geographical location on the LCCA. The results demonstrate that the costs of the pre-fabricated building can increase up to 43 %, 41 % and 101 % respectively for the construction, maintenance and demolition phases by shifting from El Paso to San Francisco. Moreover, the operation cost of the pre-fabricated building is less in Los Angeles and San

Francisco and higher in El Paso. It should be noted that these differences exist while all these locations are categorized as the ASHRAE climate zone 3 and both Los Angeles and El Paso as climate sub-category 3B (dry). As discussed in the literature review, most studies on LCCA of buildings only consider one location. Considering the substantial impacts of the location on operation cost as well as material, labor and equipment costs, it is suggested to assess the building(s) in different locations in future studies.

The sensitivity analysis of the discount rate showed its substantial influence on the total LCC. Likewise, the lifetime of analysis has a tremendous impact on the magnitude of LCC of each building. It should be noted that while the impact of discount rate is rationally more consequential with the costs linked to the end of life cycle, shortening the lifetime can lead to undervaluing the total LCC. The inflation rate of electricity cost did not demonstrate much sensitivity as it is only associated with the operation cost. However, both the studied structures have low *U-Value*s and this parameter can be more influential for other buildings and in different climates. The sensitivity analysis of the inflation rate of maintenance and demolition costs moderately affect the LCC of buildings associated with high maintenance (e.g. pre-fabricated) or demolition (e.g. masonry) costs. However, by selecting the lower discount rate this influence can become more prominent. These findings highlight the importance of carrying out sensitivity analysis in future studies.

There has been no published study on LCC of pre-fabricated FRC buildings, most likely due to the novelty of the material in the building sector and the consequent difficulties and uncertainties in obtaining the data. Cost is dynamic and collecting accurate cost data is always a challenge. In case of pre-fabricated FRC buildings, the available data is very limited and the obtained data for different costs in this study were based on manufacturing in small-scale. However, considering modular characteristic of this structure, its manufacturing process can be automated and therefore the LCC of pre-fabricated building may be reduced. Moreover, considering different *U-value*s can change the magnitude of costs of different phases for both buildings. Hence, comparing different pre-fabricated FRC buildings with other types of buildings are suggested for future studies.

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CHAPTER 7 CONCLUSIONS

Abbreviations

CdTe	Cadmium telluride
CIS	Copper indium selenide
GHG	Greenhouse gas
GHI	Global horizontal irradiance
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
LCIA	Life cycle impact assessment
LLP	Loss of load probability
MCDA	Multi-criteria decision analysis
Mono-Si	Monocrystalline silicon
NPV	Net present value
Poly-Si	Polycrystalline silicon
PV	Photovoltaic
SAPV	Stand-alone photovoltaic

7.1 Summary

The goal of this thesis was to develop a sustainable pre-fabricated sheltering and housing solution for developing countries in Africa. Toward this aim, this research was initiated with material screening and performing relevant tests and analyses for different alternatives. The material selection phase ended when a multi-criteria decision analysis (MCDA) had identified the optimum solution for the structure. The proposed structure (sandwich-structured composite) was eventually compared with a typical masonry wall in terms of different criteria. Consequently, the environmental impact associated with a building made of the proposed composite was compared with a masonry structure. The thermal performance of the building was then investigated by measuring the variations of indoor air temperature throughout the year. Subsequently, impacts of different passive cooling techniques (shading, natural ventilation, cool painting and thickness of interior gypsum plaster) were examined in different climates in terms of average indoor air temperature as well as thermal comfort of the occupants. Identifying the most effective solution of each technique and their combination revealed an optimized design for the building. Thereafter, the implementation of the proposed building was evaluated in rural areas of Nairobi, Kenya (as a case study) by determining two levels of end-user energy demand. Annual cooling and heating energy demands were then considered to keep the occupants within the comfort temperature along with evaluating the impacts of studied passive cooling techniques. Once the energy demand was determined, the feasibility of energy self-sufficiency for the studied building was investigated by sizing the main components of a stand-alone photovoltaic (SAPV) system. The impact of supply of load probability on required power of photovoltaic (PV) array was next studied by evaluating four different PV technologies. Moreover, for each PV technology, the Greenhouse Gas (GHG) emissions of the SAPV system were compared with an alternative grid extension system to highlight the environmental advantages. Finally, the life cycle cost of the proposed building was evaluated in comparison with a comparable masonry building by taking into account four phases (namely, construction, operation, maintenance and demolition) and utilizing net present value (NPV). Different sensitivity analyses were also performed to assess the influence of parameters such as construction cost, climate and discount and inflation rates. Fig. 7.1 illustrates the thesis structure and correlations of different research sections toward three dimensions of sustainability.

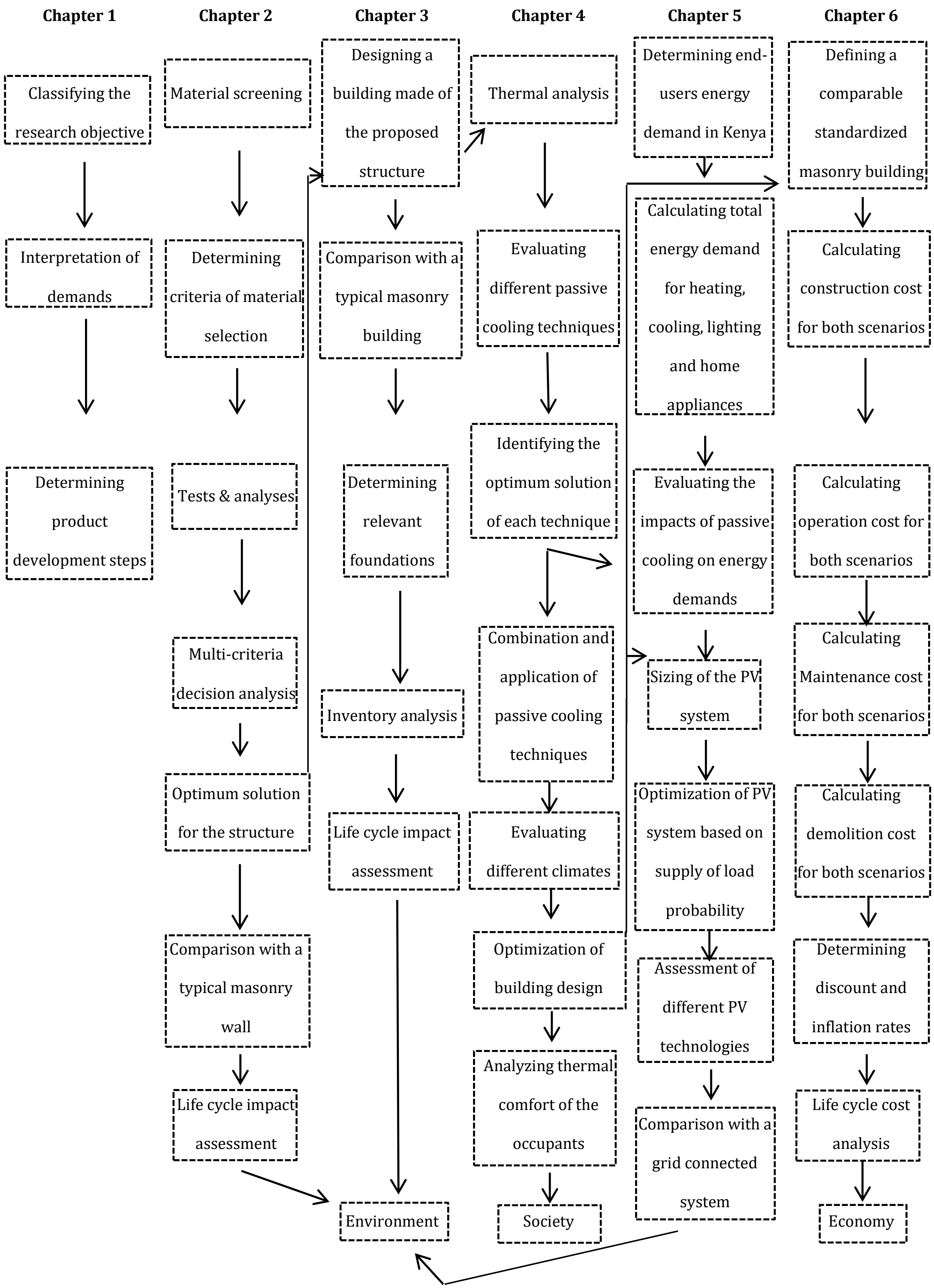

Fig. 7.1. Thesis structure toward three dimensions of sustainability

7.2 Main findings

The outcomes of this thesis answered the stated research questions in the introduction and highlighted other findings. The results of the structure development demonstrated that the proposed composite structure has considerably higher specific strength, lower density and better thermal resistance in comparison with a brick wall. However, acoustic and fire properties revealed that there still exists room for improvement. In terms of environmental and life cycle impact assessment (LCIA), the comparison was performed based on two different functional units: a unit of area as well as the whole building including the required foundations. While comparison based on the unit of area indicated 57 % less overall environmental impact of the proposed structure, this number decreased to 43 % for considering the whole building (including foundation) as the functional unit.

The analyses highlighted the environmental and economic benefits of requiring a small-scale foundation for the pre-fabricated building in comparison with masonry. On the other hand, having an identical structure for the interior and exterior walls, floor and roof turned out to be disadvantageous. From this study it is possible to conclude that pre-fabrication, manufacturing and assembly and low thermal inertia allow the use of the same panel for the interior walls as exterior walls. However, the use of these better materials in interior walls is considered as a weakness from environmental and economic points of view. Moreover, the life cycle cost analysis (LCCA) demonstrated lower demolition cost in spite of higher maintenance cost for the pre-fabricated building. This high maintenance cost was related to the shorter life span of the pre-fabricated components and implied a need for improvement. Additionally, while the pre-fabricated building presented reasonably higher construction cost than masonry, it proved to have lower operation cost in warm climates. Furthermore, the sensitivity analyses illustrated that parameters such as construction cost, climate and discount and inflation rates are highly influential in determining the life cycle cost of a building. It should be noted that the cost itself has a dynamic essence and depends on numerous factors such as implementation time, economies of scale, externalities, etc.

The results of thermal analysis pointed out a substantial impact of the presence of occupants on indoor air temperature, especially in winter. Moreover, all of the four studied passive cooling techniques (shading, natural ventilation, cool painting and thickness of interior gypsum plaster) demonstrated their effectiveness in decreasing the indoor air temperature and tackling overheating in the building; however, their performance turned out to be highly dependent upon climate. The results also highlighted inconsistencies between using peak or average of highest/lowest temperatures as well as different thermal comfort models. For the climate of Nairobi, the combination of these techniques proved to be efficient enough in providing thermal comfort for the occupants during almost all annual occupancy.

The tests and analyses of the developed structure demonstrated that the proposed sandwich composite has suitable compressive strength, density and thermal resistance to be considered as a pre-fabricated building material. Moreover, the results of thermal analysis confirmed its capability to provide thermal comfort for the occupants in a building made of this structure. Furthermore, optimizing the building by adding interior gypsum plaster not only showed positive impacts on high and low indoor air temperatures in summer and winter, but can also enhance the acoustic and fire properties of the proposed structure which were initially addressed as its problems. In addition to improving thermal comfort of the occupants, cool painting also caused a notable decrease in surface temperature, a decrease that can be important for manufacturing requirement of panels. Overall, these outcomes answer the first research question of this study confirming that sandwich-structured composite technology can be utilized in pre-fabricated buildings.

The energy analysis showed that the studied passive cooling techniques can tackle overheating in the building by cutting down the cooling energy demand significantly. In the climate of Nairobi, the optimization of the building through combination of four studied passive techniques resulted in decreasing about 84 % in annual cooling energy demand and reaching the requirements for passive houses. This answers the second research question confirming that i tis possible to fulfill passive house prerequisites by the proposed building.

Regarding the possibility of integrating a SAPV system to supply the energy demand, the sizing of the system was found on the supply of load probability. These results highlighted a substantial impact of supply of load probability on required power of the PV array for different levels of energy demand and PV technologies. A major finding of this investigation was a remarkable increase in required power of array for less than 2% loss of load probabilities (*LLP*). Taking into account the LLP and annual missing energy, monocrystalline silicon (mono-Si) demonstrated the best performance followed by cadmium telluride (CdTe), copper indium selenide (CIS) and polycrystalline silicon (poly-Si). Moreover, in assessment of environmental impacts, the environmental impacts associated with the battery in SAPV systems was pointed out that is neglected in

PVsyst software. Consequently, the results highlighted the superiority of CIS followed by CdTe, poly-Si and mono-Si in terms of GHG emissions. It was also discussed that this dominance is due to durability of thin films while Cadmium is a toxic element. Comparing with an alternative grid extension PV system, the SAPV system using CIS modules demonstrated potential reduction of about 16 tons of GHG emissions for ordinary needs scenario and around 5.8 tons for basic needs scenario during lifetime of PV panels (25 years). Taken together, these results support the possibility of integrating a SAPV system in the studied building being capable of supplying the needs of occupants in Nairobi. This solution provides the possibility of energy self-sufficiency for both basic and ordinary needs scenarios and answers to the third research question.

7.3 Key contributions

This thesis proposal was ambitious, once its implementation can enhance the quality of life of many people. Respecting the framework of the PhD program and requirements of the industrial partner, it needed to have a multi-disciplinary horizontal approach. As far as it is possible to verify there is no published article or thesis taking into account these dimensions all at once. As such this study should be of interest to a broad readership and gives a comprehensive approach to those who look for novel and sustainable sheltering and housing solutions. Willfully, sustainability is the heart of this proposal and the thesis structure was designed in pursance of meeting its prerequisites (as it is illustrated in Fig. 7.1).

The ultimate goal of this thesis was to develop a sustainable, pre-fabricated, passive, energy self-sufficient building for developing countries in Africa. Hence, the primary contribution of this thesis is the integration and fulfillment of all these aspects through a design and development process. The current housing solutions in Africa are mainly either costly eco-unfriendly masonry buildings or thermally uncomfortable timber ones. In this study, a novel sandwich-structured composite is proposed as a sustainable lightweight building material that can provide thermal comfort for the occupants. Moreover, this development has taken into consideration several aspects such as mechanical, thermal, acoustic and fire performance as well as cost and environmental impact in order to assure both the technical viability and the sustainability requirements are met.

The environmental impact assessment and cost analysis of the proposed building in comparison with a masonry one took into account the whole building including the required foundation. The former studies, and particularly those focused on developing or comparing building materials, have taken into consideration mostly a unit of area and sometimes the whole building, but without its foundation. The remarkable amount of materials and energy being used for foundations somehow reminds us the “iceberg theory”. The results of this study illustrate the need to regard foundations of buildings in sustainability assessment and, therefore, contribute to life cycle assessment (LCA) of buildings for both environmental (LCIA) and cost (LCCA) analyses.

To tackle overheating, this study compared effectiveness of various passive cooling techniques in different climates. Natural ventilation and cool paintings (if applied at construction phase) are presented as approaches free of any cost along with different types of shading. Moreover, four valuable benefits are highlighted for coating the building envelope with an interior gypsum plaster: 1) decreasing the indoor air temperature in summer; 2) increasing the indoor air temperature in winter; 3) improving fire safety properties of building envelope; and 4) enhancing sound insulation of walls. These outcomes are highly beneficial for investors, designers and inhabitants to make decision on applying which technique for cutting down the air conditioning cost. Furthermore, different indicators such as indoor and surface temperatures, stored heat and solar heat gain as well as thermal comfort models were used and interpreted to measure the impact of the studied techniques and realize the causes and effects associated with them. To being it all together, the conducted thermal and energy analyses in this study provides important insights into the passive house design that can be highly advantageous in optimization of building not exclusively for prefabs in Africa, but to tackle overheating in any building.

Relatively few published studies on sizing of SAPV systems are mainly found on cost which is a very dynamic parameter in PV world. This study, however, demonstrated the importance of supply of load probability in sizing of SAPV systems by highlighting significant advantage of considering at least 2% *LLP*. Moreover, while many of former studies have investigated environmental benefits of PV systems over alternative energy sources, this thesis compared the designed stand-alone PV system with an alternative grid extension PV system and concluded remarkable reduction in GHG emissions. This study also pointed out an issue that must be taken into consideration in the *PVsyst* software, because its calculations neglect the environmental impact of the storage battery in SAPV systems. The verified possibility of integrating a SAPV system in the proposed building is highly beneficial for electrification of remote areas in Africa where the access to the electricity grid is difficult and costly.

In view of all that has been mentioned so far, this thesis led to development of a building which is sustainable, passive, energy self-sufficient and pre-fabricated. This PhD thesis was built up under the framework of MIT Portugal program and by setting engineering systems as a focal point. Hence, beyond all scientific and technological approaches and outcomes, it was driven by a societal problem with global importance. That is why it is contrasted to typical theoretical theses that develop general, context-independent, analytical methodologies. I would like to refer to the addressed problem in this study anew. The starting point was a societal problem: housing is scarce in the world and even more so in Africa. There is a considerable portion of population without proper homes and electricity. Concerning current rate of population growth, this scarcity will become even more significant in future. The proposed sheltering and housing solution can help substantially in improving and even saving lives of many people. Moreover, bringin electricity to the rural areas creates new horizons such as internet and education for these people. This thesis, therefore, contribute to sustainable development of African countries.

7.4 Future research

The horizontal and multi-disciplinary theme of this thesis led to involvement of different fields of science. Nonetheless, there still exists a vast room for further development. While African developing countries were considered as the ultimate target for the proposed building, the global nature of product has been regarded throughout the development. Accordingly, various warm climates such as Nairobi, Mumbai, Porto, Los Angeles and San Francisco were considered as case studies in different analyses. When it comes to the implementation of the proposed building in a specific location, the requirements of target climate must be taken into consideration. Therefore, design of the building may need to be optimized with regard to that climate by going through the same development process.

The structure development of the sandwich-structured composite was based on recognized cores, matrices and reinforcements. Integrating novel solutions such as phase change materials would be fruitful in improving thermal properties of the proposed structure. Moreover, as discussed in chapter 2, developing zero ozone depleting foaming agent technologies for extruded polystyrene would be of great help in decreasing their environmental impact. Furthermore, although understanding know-how of fabricating sandwich-structured composites was a part of learning phase, their manufacturing methods are not discussed in this thesis. Evaluating different manufacturing processes and possibility of integrating automation systems would be an interesting topic to be undertaken in future studies.

As it was discussed in chapter 5, there is a notable difference among different sources of data particularly for daily average solar global horizontal irradiance (GHI). The sensitivity analysis performed for LCCA in chapter 6 highlighted the importance of reliable and valid data. It would be interesting to perform a sensitivity analysis on designing SAPV system as well to evaluate how differences in GHI data can affect the sizing of the system.

Clean water is another vitally important issue in rural and urban areas of Africa. The lack of clean water and access to adequate sanitation lead to death of many people, mostly young children. There have been attempts on utilizing solar technology to solve this problem by either extracting groundwater through a pump or running a water purification system. Further research could usefully explore the integration of a water extraction and/or water treatment system in the design of the proposed building.

The proposed design of the building was found on current housing solutions for a family of four people. The standards for required space per person differ from a country to another. Moreover, depending on the application whether it is for temporary sheltering or housing, the architectural design may need to change. Future research could usefully explore novel designs for a building made of the proposed structure by taking into account requirements of space per person in different countries and for particular applications. In addition to review the design from an architectural point of view and taking into consideration the standardized requirements, it would be interesting to look over cultural aspects of design as well.

Implementation of the proposed building is associated with numerous social concerns. The conventional methods of building construction are already regulated in African developing countries and jobs of large group of people are related to them. Bringing a new housing technology would be associated with fear of losing jobs. Besides, fabrication of this structure requires certain skills that are very different from the current ones. Furthermore, providing an energy self-sufficient housing solution for remote areas has its own challenges and consequences. Would it prevent immigration of people to big cities or lead to isolation of communities? Would it forever change ways of life or create ways for keeping them? Further research is required to answer these questions from social point of view.